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PRINCIPLES OF STREAM EROSION IN HAWAII[1]

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ABSTRACT

The steep-walled, blunt-headed box canyons and the imposing cliffs or "palis" of various parts of the Hawaiian Islands have long attracted the attention of travelers, and in some instances faulting or other tectonic factors have been invoked to explain them. It is concluded that these features are mainly the product of the normal erosional processes of the region, of which the conditions differ somewhat markedly from those of most temperate, humid parts of the earth. The principal factors are the high porosity of the rock and its susceptibility to chemical weathering, the high mean annual temperature and the rarity of great ranges of temperature, the absence of frost and the high annual rainfall of certain parts of the group. As a result, chemical weathering at elevations near the low water table dominates the development of the deeper valleys and is a controlling factor in determining their configuration.

INTRODUCTION

The surface features of the eight larger islands of the Hawaiian group are generally rugged and mountainous. Several of the islands reach elevations of more than 3,000 feet, and the twin peaks of Mauna Kea and Mauna Loa on Hawaii reach nearly 14,000 feet. The visitor to these islands is impressed especially by the extraordinary depth to which the older volcanic cones have been dissected on their windward sides and by the exceptional steepness of the side and head walls of the numerous resulting gulches (Figs. 1 and 2). In these and related characteristics, the Hawaiian landscape contains certain features less well known to physiographers than those of most temperate, continental regions, and it is the purpose of this paper to describe in outline the principal conditions and processes which have produced these striking elements of the topography.

[1] With the permission of the Director of the Bishop Museum, Honolulu.

In emphasizing the contrasts between the topography of parts of the islands and that of most temperate regions we must not conclude that the sum total of processes of stream erosion in Hawaii differs widely from those of temperate regions but must rather recognize that there is in Hawaii a considerable difference in the relative prominence of the several factors, and that in certain favored situations there result topographic features sufficiently unusual to command the attention of students and laymen alike. In other parts of

FIG. 1.—Head of branch of Waipio gulch of northeast Hawaii. Photo by Perkins, Honolulu.

the islands where the special factors play a less prominent part the topography does not differ markedly from that of other regions. Since the purpose of this paper is especially to describe the conditions of origin of the more unusual topographic types no attempt will be made to describe in detail the areal physiography of the islands nor to analyze in correct proportion the denudation of the Hawaiian group in its entirety.

Field work on which this paper is based was done by the writer as Bishop Museum Fellow of Yale University. During his stay in Hawaii in 1923 and 1924 he was the recipient of assistance and courtesies from numerous residents of the region. He is especially

indebted to Harold S. Palmer, professor of geology in the University of Hawaii, whose aid in securing equipment, advice as to localities, and friendly criticism were of inestimable value. In the preparation of this manuscript criticism and suggestions by M. R. Campbell and W. C. Mendenhall of the United States Geological Survey were of great assistance.

FIG. 2.—Detail of the cliff of north Molokai at Kalaupapa. The cliff truncating the spur in the center rises 1,800 feet from the water's edge to the apex of the triangular facet. The mouth of Waikolu gulch is immediately to the left (east). The high point of the spur still farther east is well over 3,000 feet above sea-level (see Fig. 9). Photo by Gartley, Bishop Museum collection.

CONDITIONS INFLUENCING EROSION

STRUCTURE AND COMPOSITION OF ROCKS

The major structure of the rocks of the Hawaiian Islands is simple and uniform. The entire land mass above sea-level is made up of thin basaltic lava flows lying one on another to form cones some of whose bases are as much as 40 or 50 miles in diameter and whose summits rise to maximum elevations of nearly 14,000 feet above sea-level. The submarine dimensions of the cones are enormously greater (Fig. 3). The individual lava flows are in the main from 5 to 20 feet thick, very few so far as known exceeding the latter figure over any considerable area. Most of the individual flows are

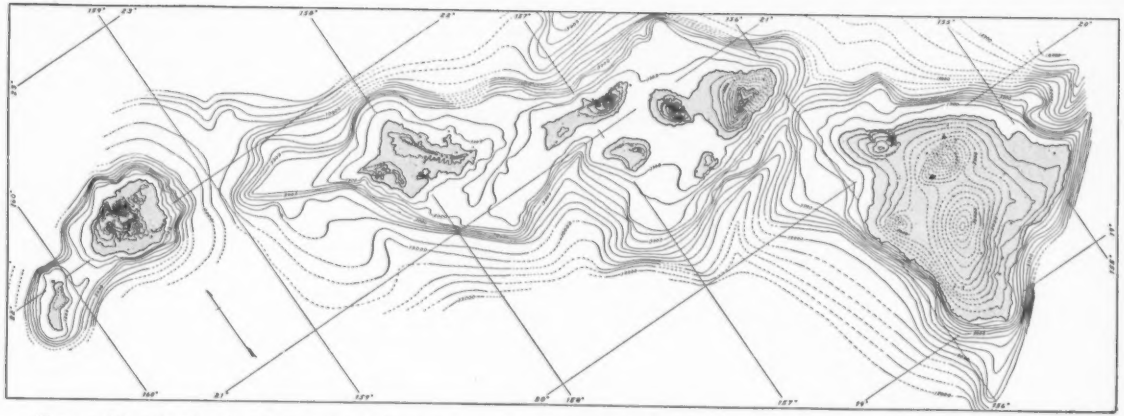

FIG. 3.—Map showing the topography of the eastern portion of the Hawaiian volcanic range. Submarine topography from U.S. Coast and Geodetic Survey chart 4102. Topography of Kahoolawe from sketch map by U.S. Coast and Geodetic Survey. That of remaining islands from U.S. Geol. Survey maps (solid lines) and generalized from other sources (dotted lines). Contour interval, 1,000 feet.

limited to one side of the cone of which they form a part, and, in general, probably have a width of considerably less than the radius of the cone. The lengths of the flows vary from a few yards up to a few miles, and the areas of historic flows on the island of Hawaii range up to 20 or 25 square miles. It is apparent that unless the old flows which have formed the various islands were of far greater extent than the historic ones, there are great numbers of slight "unconformities" between overlapping flows, but the exposures are so limited and identification of key flows so difficult that the structure gives the impression of great uniformity and parallelism.

In a few places there are thin layers of basaltic tuff, but in the main pyroclastic material is confined to the relatively small mass of the secondary craters in the southeast part of the island of Oahu and a few other restricted localities. The tuff does not differ greatly in its properties from the lava flows in so far as the forms of weathering and erosion are concerned.[1] Mechanically it is a much weaker rock; chemically it weathers in a manner similar to the basalt, though it probably decomposes more rapidly. It is somewhat less pervious than the basalt but is still a very pervious rock and so far as known has similar thermal properties.

Dikes and sills are known but are comparatively rare on most of the islands. In few, if any, places do they form conspicuous elements in the structure.

From the foregoing it is apparent that the initial land surface in Hawaii consists of rudely circular cones having radial slopes ranging from 3° to 15°. Into these simple conic surfaces, broken in a few places by smaller parasitic cones, the present valleys have been cut.

POROSITY AND OTHER PROPERTIES OF THE ROCK

Porosity is an important factor in determining the form of the ground-water table, and this in turn materially affects the growth of permanent streams. Though the lavas of Hawaii in small masses are compact and dense the rock masses of whole islands are extremely porous. The great number of thin flows, interbedded with the scoriaceous *aa* type of lava or weathered basalt, the presence of lava tubes, lava bubbles, cooling cracks, spaces due to imperfect contact

[1] C. K. Wentworth, "The Pyroclastic Geology of Southeast Oahu," *Bishop Museum Bull. 30* (1926).

between new and old flows, and joints combine to make the rocks exceptionally pervious.

On the other hand, the mass of weathered lateritic material which mantles large parts of the surface is probably somewhat more impervious, and this condition results in the development locally of small areas of badland topography and may be an important factor in the production of the high-level sloping swamps which are found on parts of central Kauai and Molokai as well as lesser parts of other islands. It is probable also that the vegetation cover of the windward slopes helps largely in the maintenance of water in the superficial parts of some of the cones.

The basalt of Hawaii appears to be relatively little subject to weathering through the agency of temperature changes. A fine-grained rock like basalt, because of its greater fineness of grain, is less subject to disintegration through differential stresses of thermal origin between the grains of different constituent minerals than is a coarse-grained rock of the same composition. The presence of moisture increases thermal conductivity and reduces the amount of differential stresses due to temperature changes. The effect of temperature changes is probably much reduced also by the very general mantling of the surface of the basalt by lateritic residuum over much of the area of the older islands.

Basalt is generally recognized as offering rather slight resistance to chemical weathering because of the relative instability of such minerals as augite, olivine, and plagioclase feldspar as compared to quartz and orthoclase.[1]

It is thought that the rate of chemical weathering of basic rocks and the rate of the extreme type of decomposition producing laterite is very greatly increased with increase in mean annual temperature, since most of the known extensive occurrences of laterite are in tropical or subtropical regions.

CLIMATIC CONDITIONS

Temperature changes at sea-level in Hawaii are slow and small in amount, and this statement applies to nearly the entire area of

[1] F. W. Clarke, *Data of Geochemistry* (4th ed.), pp. 386, 485; C. K. Leith and W. J. Mead, *Metamorphic Geology*, pp. 20–24; G. P. Merrill, *Rocks, Rock Weathering and Soils* (1906), pp. 9–29.

the islands. Though it is probable that fluctuations of greater range and rapidity take place at the summits of the higher peaks, it may nevertheless be assumed that in severity these fall far short of those of similar situations in higher latitudes on the continental areas. At no one place in the whole group of islands does the range from the mean of the warmest month to the mean of the coldest month exceed 8° F.

Frost is believed never to form below about 2,500 feet and rarely below 4,000 feet. Near the summits of Mauna Kea and Mauna Loa snow lies most of the year in protected places, and no doubt freezing temperatures are common much of the year at somewhat lower

TABLE I

EXTREME RAINFALL CONTRASTS

(Precipitation to Nearest Inch)

Station	Island	Elevation (Feet)	Distance (Miles)	Year	Annual Rainfall (Inches)
Waialeale	Kauai	5,075	15	Mean	476
Waiawa	Kauai	35		Mean	22
Puu Kukui	Maui	5,000	8½	Mean	370
Camp No. 7	Maui	90		Mean	16
Puu Kukui	Maui	5,000	8½	1918	562
Camp No. 7	Maui	90		1912	2.46

levels. Nevertheless, these elevated areas are small relative to the whole extent of the islands, and it is evident that frost is of nearly negligible importance as a weathering agent affecting the general erosional development of the group.

The dominant factor in the rainfall conditions of the Hawaiian group is their position within the tropics and in the zone of the northeast trade winds which are abruptly cooled in passing over the mountainous summits. Thus in spite of the fact that trade winds are normally drying winds, large parts of the windward and summit areas receive a very heavy rainfall and certain localities rank among the rainiest places in the world. On the other hand, many districts on the leeward shores are extremely dry (see Table I). Altitude has an important effect on the rainfall. It has long been recognized that the rainfall on windward slopes increases with altitude for several

thousand feet but that the maximum rainfall is reached considerably short of the summits of the higher islands. Conditions on the leeward slopes are so varied that it is impracticable to formulate even a rough law for the altitude-rainfall relationship. The mean rainfall for the islands is probably somewhat over 100 inches per annum.

As a factor in erosion the vegetation cover is of considerable importance and may be included as a secondary subdivision under "Climate." Contrasts in vegetation are very great between the rainy windward districts and the dry leeward slopes. It is probable that the thick cover of ferns and other plants which forms a true tropical rain forest in some parts exerts a considerable influence on the processes of erosion. The detailed character of this influence is unknown. It is not apparent that the vegetation cover exerts more than a slight local effect in preserving the conic slopes, and it is difficult to believe that the broad lines of the larger gulches or the profiles of their walls are determined to any considerable extent by the presence of plants. Future detailed studies are needed, however, to answer this question and to solve other problems connected with the vegetation cover of the islands.

PROCESSES OF EROSION

TYPES OF WEATHERING

The two principal types of physical weathering, as known in most temperate regions, are those due to temperature changes in the rock and those due to the freezing of water in crevices. The first class includes exfoliation proper (thermal expansion spalling at the surface of the ground) as well as splitting and crumbling. The absence of freezing temperatures below 2,500 feet in Hawaii and their comparative rarity below 10,000 feet during much of the year makes the wedgework of ice a negligible factor over much of the group. Moreover, the very low diurnal and seasonal temperature fluctuations and the fine grain of the basalt flows reduces weathering due to temperature changes to negligible proportions.

Much of the altered superficial basaltic residuum of the island has a spheroidal structure resulting from weathering, and in places spheroidal masses of basalt are strewn on the ground. There is little

doubt that the spheroidal structure results from differential volume changes which affect the surface parts more severely than the interior. In regions where these structures are confined to rocks exposed at the surface they are probably in part due to temperature changes. In Hawaii, however, where the spheroidal structure is developed to a considerable depth below the surface, and probably in many other regions, the volume increases are caused by chemical alteration and

FIG. 4.—Detail view showing spheroidal weathering. Photo by H. S. Palmer, Honolulu.

FIG. 5.—"Boulders" resulting from spheroidal weathering. Photo by H. S. Palmer, Honolulu.

hydration affecting the superficial rocks. Attention has recently been called to the need for more precise application of the term "exfoliation," and for recognition of the comparatively small part temperature changes play in what has loosely been called "exfoliation" but is more properly "spheroidal weathering" (Figs. 4, 5, and 6).[1]

[1] E. Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806; C. K. Wentworth, "Geology of Lanai," *Bishop Museum Bull. 24* (1925), p. 24; also "Pyroclastic Geology of Oahu," *ibid. Bull. 30* (1926), p. 30.

The conclusion seems justified that physical weathering as a whole is very unimportant in the Hawaiian Islands, and that at low and intermediate altitudes it is wholly subordinate to chemical weathering. It is probable that the importance of physical weathering increases in the higher parts of the group and may be locally dominant, but these exceptions scarcely invalidate the general conclusions.

FIG. 6.—Detail of boulders in Mapulehu stream, Molokai. The rounding of these boulders is more largely the result of weathering than of abrasion.

Chemical weathering consists chiefly in the transformation of the silicates and other minerals of igneous rocks into the carbonates, sulphates, chlorides, and other salts of the constituent metals and, in the hydration and solution of the salts or original compounds. The principal products are iron oxides, carbonates of calcium and magnesium and clay. Discussion of the nature of these changes is beyond the scope of this paper, and it is sufficient to point out certain controlling conditions.

All these alterations require the presence of moisture. In general, they probably take place most rapidly in the zone just above and

just below the water table. In contrast to its effect on physical weathering, vegetation is an aid to chemical weathering. The very great porosity of the Hawaiian rocks, the high average rainfall, the relative ease of decomposition of the minerals composing the basalts, and the high mean annual temperature combine to produce very rapid chemical weathering in the islands, a condition shared, of course, with many other tropical regions. It must be emphasized that this weathering is wrought by the interplay of a number of factors which operate through a single fundamental agent, water. Remove this agent and chemical weathering is largely eliminated.

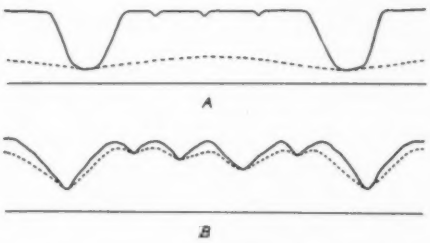

FIG. 7.—Water table diagrams. (A) Showing relation of groundwater to topographic surface in Hawaii. (B) Showing relation of groundwater to topographic surface in more humid parts of United States mainland.

As a result of the great porosity of the rocks, the water table in Hawaii is characteristically very low (Fig. 7). Over large parts of the group the surface rocks are dry and shallow wells yield no water. In such situations it is only near the bottoms of the deepest ravines that perennial springs are found. Here also in the water-table zone, weathering is far more rapid than on the higher slopes or at the summits of the peaks. On the windward slopes where the rainfall is higher there is a considerable amount of surface water in transit at high levels as well as low, and it is probable that a considerable amount of weathering goes on at all elevations (Fig. 8). There is a significant difference, however, between physical weathering and chemical weathering. The latter lacks an agency by which rock fragments are thrown down or displaced to any appreciable extent. It is more insidious in its action, and only in its more ad-

vanced stages produces material which assumes under the force of gravity low angles of repose.

The two factors mentioned above, the greater activity of weathering near the water table and hence at low altitudes, and the capacity of rock partially weathered chemically to stand at high angles when physical weathering is inoperative, combine to produce slopes of great uniformity and steepness. The declivity of the slopes is the angle of stability for the unweathered or moderately weathered material of the cliffs. The uniformity of steepness to the very top of the slope is a result of nearly uniform wastage from the base of the cliff, either by weathering or by stream transport. In most regions the upper parts of slopes are affected by weathering processes of a type which are progressively more active at higher altitudes, and the higher slopes have also been longer subject to such action. Both of these factors tend to produce gentler slopes at the top of any given profile and hence convexity of the upper part of the profile. On the contrary, agencies which are more active at lower levels are responsible for the forms of the deeper parts of valleys which in general are of necessity concave. In most parts of Hawaii the processes which promote more rapid wastage at lower levels are dominant, and the wastage at the lower levels is shown in the nearly uniform slopes of cliff faces. It is evident that much of the foregoing discussion is applicable to the development of sea cliffs as well as to the forms which result from the work of streams.

FIG. 8.—Fall of water trickling down headwall of Moanalua gulch, Oahu.

In the more striking of the "box canyons" of Hawaii convexity of profile is confined to a very narrow zone at the top where the much-weathered mantle rock forms gentler slopes a few feet in height (Fig. 9). It is evident that the processes of weathering and transport which are favored in the lower parts of a valley cannot become operative until valleys of considerable depth have been developed. Over large parts of the islands where there has been little dissection of the cones, or where erosion has been slow and general, the topography does not differ greatly from that in rainy temperate regions and the slopes are no steeper than in such regions. In such

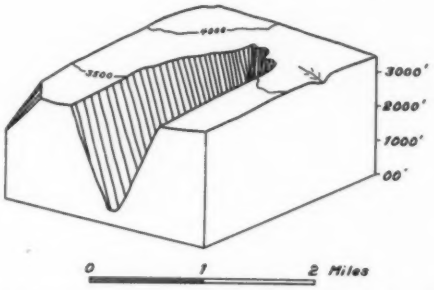

FIG. 9.—Block diagram of head of Waikolu Gulch, North Molokai, east of Kalaupapa (see Fig. 2).

situations the predominance of the concave portions of profiles over the convex portion, which is so striking in the dissected parts, is not evident. It is in the striking contrast between the essentially concave topography of the deeply dissected areas and the more normal topography of the less eroded areas that the Hawaiian landscape is conspicuous.

EARLY STREAM WORK

The percentage of the total rainfall in Hawaii which reaches the sea by underground routes is unusually large. Valleys must reach a great depth in most places before they tap the ground-water body so as to support permanent streams. On the other hand, the very heavy rainfall of certain districts and the steepness of some of the initial slopes produces a heavy ephemeral run-off which, as elsewhere, tends to become localized and to result in extensive gullying.

The superior effectiveness of both weathering and rain wash at altitudes somewhat above sea-level brings about the development of gullies first at some point in the midslope of the volcanic cone, whence increase in length takes place at both ends.[1] In some instances the gully course is determined by the lateral margin of a lava flow, but since this itself had assumed a consequent course the distinction between this type and the usual consequent stream has little significance. The elevation of most effective gullying probably differs greatly according to the configuration and slope of the surface, but it will evidently be less than the elevation of maximum rainfall and is probably not over a thousand feet on most of the islands.

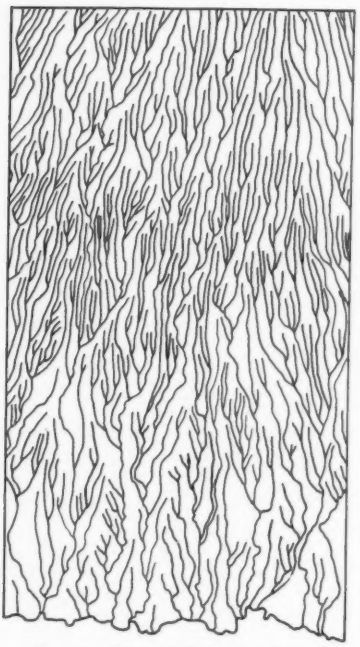

FIG. 10.—Map of drainage of portion of Honomu quadrangle on the northeast coast of Hawaii, a young drainage pattern.

The early part of the drainage history may be regarded as that characterized by many straight, shallow, radial gullies carrying water only after exceptional rains and extending neither to the summit peak nor to the seaward margins of the cone. In this respect Hawaii does not differ greatly from most regions except in the great regularity of pattern controlled by the nearly uniform slopes of the zones. Growth in length of the gullies takes place more rapidly at the lower end than at the upper end, and presently the lower ends of the gullies reach the coast (Fig. 10). Simultaneously with the growth in length, valley deepening goes on at a rate determined by the amount and duration of stream discharge. With the deepening

[1] N. E. A. Hinds, *Science*, N.S., Vol. LXI, No. 1577 (1925), p. 317.

and widening of gullies there is a concentration of drainage in fewer channels, and the number of valleys developed at the coast is less than those some distance up the slope.

An important phase of the development of stream valleys is the competition which takes place between adjacent streams. This competition commences long before there is any apparent conflict between the two streams at the surface, and is based on their mutual conquest of both direct run-off and ground water. In the case of adjacent streams fed exclusively by direct run-off with no effect from ground water, the proportions of water received from the common interfluve area depend on the relative areas topographically tributary to each stream. In the case of adjacent streams fed wholly by ground water, the proportions of water received by each depend on the area and surface slope of the water table tributary to each. The slope is far more critical in the latter case than in the former since, in the latter case, the divide is itself composed of the fluid, water, and its position is readily influenced by change in the relative flow to the two streams. Few, if any streams, even ephemeral ones, are wholly independent of ground water, and competition between streams is very largely carried on in terms of ground water.

Very soon after the position of a gully has been fixed and long before it becomes a perennial stream, the aid of ground water is felt. With each increase of depth is an increase in the number, size, and duration of flow of ephemeral springs and seepages which prolong the flow of such streams. After the stream has become permanent, each increase in depth results in the steepening of the slope of the adjacent water table and in increased inflow to the stream. Since flow at the surface under similar conditions is more ready than flow through the rocks, each underground water body, whether temporary or permanent, which is tapped and then becomes progressively drained, offers henceforth readier outlet to adjacent water bodies and the process is cumulative. Moreover, each slight increase in the number of days per year of flow of an ephemeral stream (just as surely as increase in the average flow of a perennial stream) increases its potency to degrade its channel and thus, in turn, to make still further increase in its draft of surface or ground water. In regions of relatively impervious rocks where the movements of ground water

are less continuous and more irregular, the effects of slight increases in depth, though real, may be far more feeble and far more likely to be nullified by other obscure factors than in regions of very porous rocks.

In the latter regions, and especially in Hawaii where the work of various students has shown the great ease of movement of underground water, the effects of slight deepening of stream valleys are likely to be pronounced and far reaching. In such a situation where the ground-water body between adjacent stream valleys has the form of a low simple arch, of which the crest is determined by simple equilibrium between the two lateral zones of outflow, the effect of slight deepening of one valley is likely to be felt in an almost immediate shift of the crest away from the stream in question, with a consequent increase in flow to that stream. The general principle affects the valleys of streams which do not reach perennial ground water as surely as it does those cut to the water table, though the statement of its conditions in the former case would be somewhat more complicated.

From the foregoing discussion it is apparent that the competition between adjacent streams in Hawaii is more largely a subterranean strife than in many regions. The effectiveness of underground drainage and the ever increasing headway which is afforded by slight advantages in depth seem to explain the tendency for a few great gulches to be deeply cut in the surface of a cone where the broad, tabular interfluves are scarred by a few gullies seemingly in every way as favorably situated as the gulches, but vanquished in the race.

The capacity of deep valleys in regions of porous rock to inhibit the growth of small valleys within their sphere of influence by underground theft of their waters is largely responsible for the rarity of tributaries to the younger gulches (Figs. 11 and 12). In turn the infrequency of development of tributaries to such gulches is one of the causes for the steep, unbroken character of the upper walls of the gulches and for the abruptness of transition from the valley walls to the undissected cone surface (Fig. 13). Such tributary channels as do exist commonly have two distinct portions of their courses, that developed in a consequent direction down the steep side wall of the gulch and that developed consequent to the main cone slope

(Fig. 14). Such courses result when master-gulches encroach laterally on lesser channels and appropriate their upper courses and also by consequent development of the entire tributary channel on the two types of slope. In both cases there result some very striking hanging valleys.

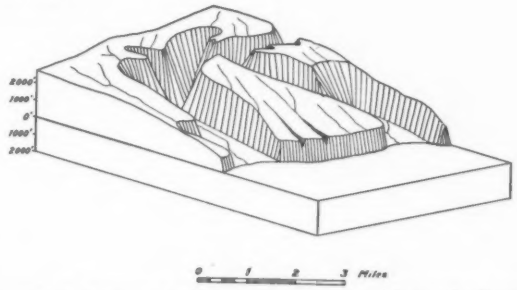

FIG. 11.—Block diagram of Waipio and Waimanu gulches and adjacent slopes of Northeast Hawaii.

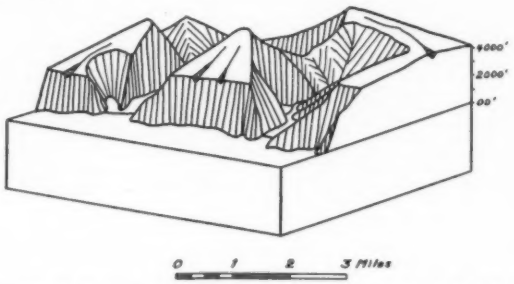

FIG. 12.—Block diagram of Pelekunu-Wailau section of north Molokai. The profound erosion of the volcanic cone surface and the facet-like remnants of the peripheral parts of spurs are well shown in this district.

In many regions piracy is an important factor in the development of complicated drainage systems. In Hawaii, because of the effectiveness of the underground drainage during a long period in the early development of drainage surface, piracy which leaves its mark in the surface outlines of the drainage is comparatively rare, except for the type mentioned in the preceding paragraph. Other factors which tend to reduce the amount of piracy are the homogeneity of the basaltic cones, the simplicity and regularity of the

initial surface, and the absence of sufficiently pronounced orogenic movements.

The very pronounced growth of a few master-gulches as a consequence of the effective underground drainage produces a type of permanent drainage system which has been described as coarse in texture.[1] A familiar example of the opposite or fine texture of dissection and drainage is shown in clay badland topography. The de-

FIG. 13.—View downstream in Maunalei Gulch, Lanai. This valley is evidently much younger than that shown in Figure 14, though the two are of essentially similar form.

pendence of these patterns on the porosity of the rocks has been cogently stated by Kayser.[2] In many of its characteristics the process of land sculpture in Hawaii and in basaltic rocks generally, where chemical weathering is dominant, is very similar to the same process in typical karst regions as pointed out by De Martonne.[3] This similarity results from the lowered ground-water table and the dependence of weathering on moisture in both types of region.

[1] C. A. Cotton, *Geomorphology of New Zealand*, Part I (Wellington, 1922), p. 67.

[2] E. Kayser, *Lehrbuch der Geologie*, I. Teil, Vierte Auflage (Stuttgart, 1912), pp. 361–62.

[3] E. de Martonne, *Traité de Géographie physique* (1913), p. 530.

VALLEY GROWTH

The forms of valleys which have been long in existence depend on the rate of growth of various parts. This growth is commonly considered under the heads of "Deepening," "Lengthening," and "Widening." In many regions the upper parts of the lateral walls of valleys are subject to processes of weathering and slumping which

FIG. 14.—View looking west over Pearl Harbor, Oahu, from Tantalus Peak. The valley in the foreground is typical of many that trench the southwest slope of the Koolau Range. Note the regular development of lateral gulches (see Fig. 13). Photo by Baker, Honolulu.

greatly modify their forms. The relative stability and slight modification of the upper head and side walls of many Hawaiian valleys which has been described above is one of their most distinctive features. In the recession of these walls a nearly constant angle is maintained, namely, that of stability of the relatively little-weathered material.

As a consequence, the forms of Hawaiian valleys are controlled to an exceptional degree by the rate of removal of material from their lower parts, and hence both widening and lengthening are essentially dependent on deepening during a long period in the valley's history. The headward limit of effective transport of débris in

these valleys is relatively low though the presence of many deep valleys without permanent streams indicates that it is somewhat above the perennial water table. This limit of effective transport tends to be carried headward by erosion along a grade which has the characteristically low angle of the Hawaiian water table. Extending inland from this point is the steeply inclined longitudinal profile of the head of the valley which in many cases is nearly if not quite as steep as its lateral walls.

Most river basins are of somewhat greater extent longitudinally than laterally because of the more effective erosion down the steeper slopes from the highest parts of the land. Hawaiian valleys likewise grow in length more rapidly than in width, partly because of the steep initial slopes of the cones and greater effectiveness of slope wash in that direction, but also because of the more effective inflow from the higher interior parts of the water table. Here the latter factor is relatively more effective than in regions of less permeable rocks.

In a valley where active downcutting is dominant the bottom will tend to be V shaped. If the stream is sufficiently sluggish to swing laterally, widening will commence. The same effect will result if the base of the valley walls is subject to marked weathering. In the islands, where chemical weathering is dominant at lower elevations, the rocks of valley walls are apparently attacked with increasing rapidity as the water table is approached, and somewhat before the stream becomes permanent the effect of widening is seen. The pronounced sapping of the lower walls due to this cause, combined with the work of the stream, is responsible for the steepness and nearly uniform declivity of the slopes. It is impossible to estimate the relative importance of the sapping due to more rapid weathering near the water table and of the transportation by the stream itself with its increased tendency toward lateral cutting as it approaches lower grades, in bringing about the widening of the valley bottom, but it is evident that both factors are operative to some degree in nearly all the valleys. It is probable that weathering is more effective at first and that stream planation becomes more important later in determining the rate at which material is removed from the foot of the valley wall.

Both these factors involve the presence of water, and a rough measure of their effectiveness may be found in the number of days per year of stream flow or of saturation of the lower valley slopes. There are all stages between permanent streams and those which flow but once or twice a year. Similarly, there are all stages between those parts of the valley slopes which are constantly saturated and those which are wet during a few days each year. It is apparent that as both weathering and transportation are so critically aqueous proc-

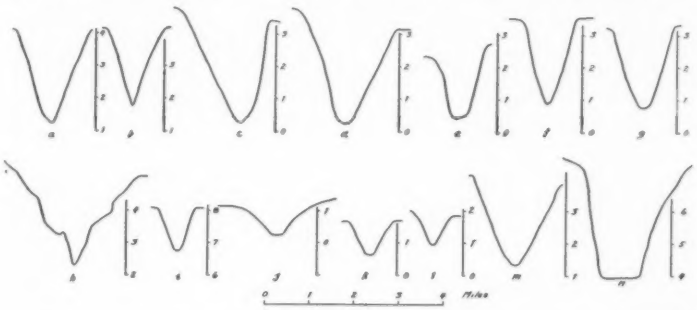

FIG. 15.—Cross-profiles of valleys in Hawaii and United States. Vertical exaggeration, 4 times. (*a*) Wainiha valley, Kauai; (*b*) Olokele Valley, Kauai; (*c*) Pelekunu Valley, Molokai; (*d*) Wailau Valley, Molokai; (*e*) Kahawaiiki Valley, Molokai; (*f*) Waikolu valley, Molokai; (*g*) Waipio, Hawaii; (*h*) Grand Canyon of Colorado near Yuma Point; (*i*) Yellowstone Canyon in Lat. 44°–46′; (*j*) Potomac water gap at Harpers Ferry, Maryland; (*k*) Wills Creek gap, West Cumberland, Maryland; (*l*) "Breaks of Sandy" gorge of Russell Fork of Big Sandy River, Kentucky; (*m*) Crawford Notch, New Hampshire; (*n*) Yosemite valley, California.

esses, the valleys of Hawaii are extremely responsive to small differences in the relationship of the water table to the valley bottom.

In those valleys where transportation equals weathering and the valley bottom is swept clean, the process of deepening reaches its maximum rate for the existing amount of water. In a broad way this condition is confined to the drier parts of Hawaii, where rocky channels are swept by torrential streams following occasional storms, and where deepening on the whole is less rapid than in the moist parts. In the more rainy parts the débris produced by weathering forms talus accumulations which flank the side slopes and smooth the transition between these and the bottom of the valley. As a

result the bottoms of many Hawaiian valleys approach a U shape, and their similarity in form to glaciated valleys is enhanced by their depth and the uniform steepness of their walls nearly to the top (Fig. 15).[1]

Conditions of transportation in Hawaii do not differ notably from those in the headward and piedmont sections of streams in other regions. There are no long and no old rivers in Hawaii, therefore no long or well-marked flood plains. Such aggraded valley bottoms as exist are characterized by the relatively imperfect sorting of the alluvium and by the imperfect demarcation between the alluvium of the plain, the colluvium of the adjacent slopes, and the talus flanking the steeper cliffs.

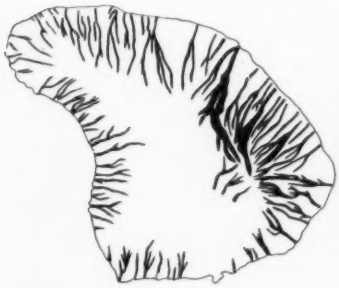

FIG. 16.—Map showing dissection of Lanai. Areas where the original volcanic surface has been destroyed are shown in black. This is a relatively young island.

FIG. 17.—Map showing dissection of southwest Kauai. Areas where the original volcanic surface has been destroyed are shown in black. Kauai is one of the older islands of the group.

PROGRESS OF EROSION

The slow widening of the upper parts of Hawaiian valleys is responsible for the preservation of large areas of the original cone surface after a few deep valleys have been cut in it. The part of a cone normally tributary to any one stream is a sector having its apex at the summit of the cone. Since the grade of the streams is

[1] T. C. and R. T. Chamberlin, "Certain Valley Configurations in Low Latitudes," *Jour. Geol*, Vol. XVIII (1910), pp. 117–24.

much less than the slope of the cone the valleys commonly have their deepest parts somewhat inland from the coast and, as a result, the upper margins of the valley converge inland, if they converge at all, less rapidly than do the margins of the sector. Hence the cone surface is commonly destroyed and the walls of adjacent valleys first merge at a point well inland from the coast. This process may continue until the entire summit area of the cone has become dissected

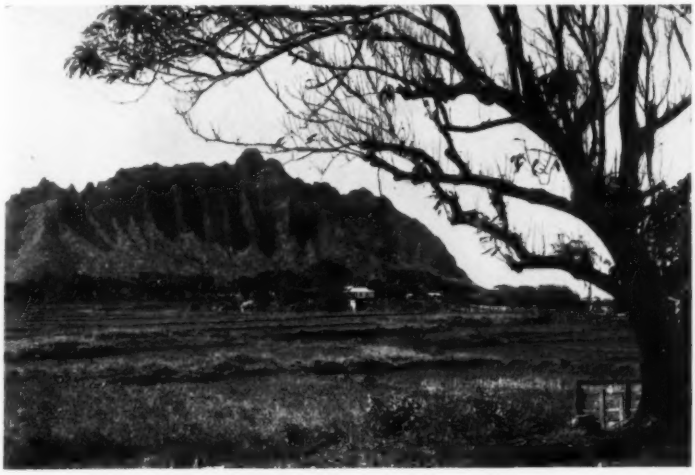

FIG. 18.—View of Kanehaolani, a knife-edge spur extending to the northeast Oahu coast. The "washboard" topography described in the text is well shown in this picture. Photo from Hawaii Photo Materials Company, Honolulu.

before the triangular flow-slope facets near the coast have been materially modified (Figs. 16 and 17; see also Figs. 11 and 12).[1] The knife-edge ridges between adjacent valleys and the steep spires which are developed in places by the converging of erosion from several directions are relatively persistent because of the effectiveness of underground drainage and the absence of frost and other agencies of physical weathering (Figs. 18 and 19). It is apparent that the location of most rapid destruction of the cone surface depends not

[1] C. K. Wentworth, "Pyroclastic Geology of Oahu," *Bishop Museum Bull. 30* (1926), p. 9.

only on the shapes of the valleys in relation to the circular form of the cones, but also on the distribution of rainfall and run-off in relation to elevation, and hence differs considerably from island to island.

In the early stages of the growth of deep valleys the steep walls are commonly nearly straight. In places where they are actively

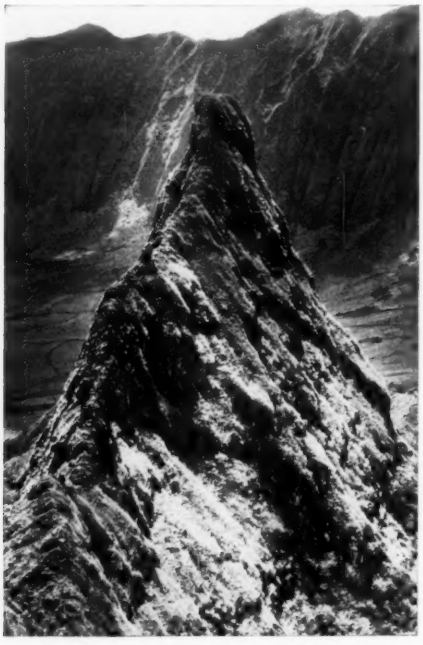

FIG. 19.—Near view of the summit of Puu Olomana looking toward the fluted pali cliff of windward Oahu southwest of Waimanalo. Photo by Oliver Emerson.

attacked at the base by stream erosion they remain nearly straight for a long time, but in other situations where they are not so undermined, irregularities develop on them of a sort which has been referred to as "washboard topography."[1] These consist of large grooves extending down the steepest slopes of the valley walls which are essentially tributary valleys consequent to the existing surface.

[1] H. S. Palmer, "Lapiés in Hawaiian Basalts," *Geograph. Rev.*, Vol. XVII (1927), p. 630.

They have been described in some detail by Palmer in the paper cited, and are shown in several of the plates accompanying this paper. These flutings appear to be the result largely of solution by the small stream of water which trickles at times down the axis of each, and ultimately may develop into more deeply cut tributary valleys which become extended headward into the upland. The only apparent cause of the uniform spacing which makes this "washboard topography" so striking in appearance is the uniformly permeable character of the rocks and the high angle of their axes which renders competition between adjacent flutings for surface and ground water relatively ineffective. A similar condition is seen in the early development of badlands except that uniform imperviousness is substituted for perviousness.

FIG. 20.—Map of drainage of Waimea-Makaweli basin and adjacent areas, Kauai; a mature drainage pattern. Consequent drainage of coastal districts east and west of the lower Waimea and conical remnants in the headwater portions of the basin leave little doubt that this drainage system is the result of evolution from a simple consequent pattern such as is common in most parts of Hawaii.

Little is known of the rate of land reduction in Hawaii. An attempt made by the writer to estimate the rate of erosion on the island of Lanai yielded the rate of one foot in twenty-nine hundred years.[1] Because of the relative proximity of the whole area of the islands to the sea, the high average elevation, and the high rainfall, the rate of erosion would naturally exceed that of most continental areas and the figure given seems conservative. A discussion of amounts of dissection in the islands has been presented in an earlier paper.[2]

[1] C. K. Wentworth, "The Geology of Lanai," *Bishop Museum Bull. 24* (1925), p. 30.

[2] C. K. Wentworth, "Estimates of Measure and Fluviable Erosion in Hawaii," *Jour. Geol.*, Vol. XXXV (1927), pp. 117–33.

No island of the group has reached a stage of development as a whole past mid-maturity, and most of the cones are still in topographic youth. The peculiarities of the erosional processes in Hawaii which have been here described and which are somewhat similar in many tropical lands of similar rocks are most pronounced during the early stages of erosion, and as erosion proceeds the conditions and resulting land forms tend to approach those of other regions (Fig. 20). Hence the topographic features of the older islands probably differ less from those of temperate regions than do those of the less dissected and younger ones.

ISOSTASY AND MOUNTAIN BUILDING

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ABSTRACT

The purpose of the paper is to formulate a working hypothesis of isostasy that will be acceptable to both geologists and geodesists. Most of the discussion is devoted to the removal of two obstacles that have caused much confusion, the belief that the geodetic calculations can be used to define the degree of crustal balance, and the claim that the theory of isostasy conflicts with the geologic concept that the folding in mountains is due to regional compressive stresses in the earth's crust.

INTRODUCTION AND SUMMARY

The theory of isostasy, which regards the crust of the earth as tending to float upon a deep-seated plastic zone, has long been given attention by both geodesists and geologists, and much evidence concerning the theory has been discovered. In general, the result of the work has led to a wide acceptance of the general theory of isostasy, but a marked divergence is apparent between the geodetic and the geologic working hypotheses of isostasy, or definitions of the degree of crustal balance. Geodesists, who use the theory to calculate the direction and intensity of gravity, find that very satisfactory results are obtained from computations based upon a working hypothesis that assumes a crustal balance that is nearly perfect. In other words, they consider the crust to act almost as if it were composed of small vertical columns floating independently of one another. Geologists, however, cannot accept this hypothesis because of evidence such as the record of the formation of a valley of erosion, which shows that a large mass may be removed from a portion of the crust without causing a local uplift of the lightened portion, or valley floor. Thus, geologists are inclined to believe that the tendency of the crust to float is not manifested in any detailed way, but is shown only by gentle warpings where large masses are added to or taken from part of the crust.

An attempt to bring together these divergent opinions of geolo-

gists and geodesists forms the first part of this paper. A working hypothesis of isostasy is formulated which seems to meet the requirements of both geologists and geodesists. In arriving at the statement of this hypothesis the step that removes most of the difficulty is the conclusion that the geodetic data cannot be used to define the degree of crustal balance, but only to test the theory of isostasy.

In addition to the difference of opinion concerning the degree of balance of the crust, there has also been considerable disagreement between geologists and geodesists in applying isostasy to the study of the formation of folded mountain ranges. The accepted geologic theory is that the folding is due to regional compressive stresses in the crust, but it has been claimed that this concept is incompatible with the theory of isostasy. This claim has been the source of considerable confusion, because, if it were true, there would be a large amount of geologic evidence opposed to the theory of isostasy. Accordingly, the second part of this paper is devoted to a discussion of this claim, and it is concluded that the theory of isostasy is not in conflict with the geologic theory of mountain building set forth above.

ISOSTASY

PRELIMINARY REMARKS

In 1889 the term "isostasy" was proposed by Dutton:

> If the earth were composed of homogeneous matter its normal figure of equilibrium without strain would be a true spheroid of revolution; but if heterogeneous, if some parts were denser or lighter than others, its normal figure would be no longer spheroidal. Where the lighter matter was accumulated there would be a tendency to bulge, and where the denser matter existed there would be a tendency to flatten or depress the surface. For this condition of equilibrium of figure, to which gravitation tends to reduce a planetary body, irrespective of whether it is homogeneous or not, I propose the name isostasy.[1]

Accordingly, isostasy, as originally defined, describes an ideal condition of equilibrium which would result if there were no strain, or, more precisely, if there were a state of hydrostatic stress in the earth's crust. Present usage of the term, however, denotes the degree of equilibrium that actually exists in the crust.

[1] G. R. Putnam, "Condition of the Earth's Crust and the Earlier American Gravity Observations," *Bull. Geol. Soc. America*, Vol. XXXIII (1922), p. 290.

In order to keep clearly in mind what is known concerning the existent isostatic equilibrium it is useful to adopt Barrell's distinction between the general theory of isostasy and the various working hypotheses of isostasy.[1] Thus there will be avoided the error of dismissing the broad concept of isostasy because one cannot accept any of the definitions of isostatic balance.

The general theory of isostasy holds that there is a tendency toward the attainment of the ideal isostatic condition defined by Dutton. The extent of this tendency is indicated by certain broad limits which are accepted by almost everyone. On the one hand, it is believed that the light continental portions of the crust owe their elevation to the fact that they are balanced against the heavy oceanic portions. On the other hand, details of topography, such as mountains and valleys, are certainly not the result of a gravitative balance between the portions of the crust under these features. As stated by Gilbert: "Mountains, mountain ranges, and valleys of magnitude equivalent to mountains, exist generally in virtue of the rigidity of the earth's crust; continents, continental plateaus, and oceanic basins exist in virtue of isostatic balance in a crust heterogeneous as to density."[2]

The various working hypotheses of isostasy attempt to define more closely the degree of isostatic equilibrium in the crust. The evidence supporting these various hypotheses falls into two main classes: the geologic and the geodetic. On the following pages an attempt is made to review this evidence and to arrive at a working hypothesis of isostasy that is consistent with all of it.

THE GEOLOGIC EVIDENCE OF ISOSTASY

There is abundant evidence of horizontal transfers of mass in the crust, as, for example, the evidence that erosion has removed material from elevated regions and deposited it as deltas or other loads at lower levels. If the crust of the earth floats upon a subcrustal stratum, these transfers of mass should cause vertical movements of the crust analogous to those which follow the loading or unload-

[1] Joseph Barrell, "The Status of the Theory of Isostasy," *Amer. Jour. Sci.*, 4th series, Vol. XLVIII (1919), p. 293.

[2] G. K. Gilbert, "The Strength of the Earth's Crust," *Bull. Geol. Soc. America*, Vol. I (1899), p. 25.

ing of a raft. Accordingly, the building of a delta or the carving of a valley can be looked on as tests of isostasy. Though in most cases a large part of the records of such tests is lost, the subject of isostasy is fortunate because one of the tests occurred at such a recent period that the record of it is still fairly complete. This test was the loading of ice on certain areas as continental glaciers, and the subsequent removal of this load. The uplift which followed the retreat of the ice sheets has been carefully studied in both Europe and North America, and most authors conclude that the close association in time and place between the uplift and the recession of the ice is proof of the action of isostatic adjustment. The quantitative relations between cause and effect, and the observed lag are features which especially indicate isostatic adjustment instead of elastic response. Particularly in Europe, where a vast number of islands and deep fjords yield many opportunities for observation, a strong case for isostatic adjustment has been prepared.[1]

In addition to furnishing this general support for the theory of isostasy, the glacial evidence may be used to define the isostatic balance of the crust. For geologic purposes such a definition should indicate the nature of the movement that would follow the placing of a certain load upon the crust of the earth. A few general considerations concerning this movement will show the terms in which it is best expressed. The evidence of crustal rigidity makes it certain that a depression caused by loading would not in general be local, that is, restricted to the loaded area. The resulting movement would no doubt be similar to that obtained by placing a load upon a thin sheet of ice, which causes a depression extending beyond the load, so that, due to the rigidity of the ice, the load is partly supported by the buoyancy of the ice on all sides. Obviously the amount of the load must also be considered. Accordingly, a hypothesis of isostasy should indicate the amount of loading necessary to cause isostatic adjustment, and also the distribution of the adjustment with respect to the load. In addition, the rate of application of the load should be considered as suggested by the lag in the isostatic adjustment following the removal of the continental ice sheets. Other factors might also modify the effective rigidity of the earth's

[1] F. T. Thwaites, "Outline of Glacial Geology," Manuscript, 1927.

crust. However, it is useless to introduce many complicating terms in the definition, because all that can be expected is a crude estimate of the degree of crustal balance. The following paragraphs show a method of formulating a working hypothesis of isostasy which expresses merely the load necessary to cause a crustal depression and the extent of this depression. For brevity, only part of the evidence is given, as it is felt that the reader will agree with the general conclusion reached, and modifying refinements of the figures seem superfluous.

The illustration of the loading of a thin sheet of ice on a lake may be carried a little farther to explain the evidence to be given. If several rocks were placed on the ice it would be possible to determine the size of the sheet contributing to their support by measuring the area of the depression. A single portion of the depressed sheet under one of the rocks would not be in independent balance, but the whole of the depressed sheet would. If the rocks were removed we might also estimate the size of the independently balanced portion of the ice by noting the water marks on the rocks, which would be present if a pool of water had collected in the depression. A few of the rocks that had been close to one another would have markings showing little differential movement, but as more were examined the evidence of warping would be clearer. Geological records of the uplift following the removal of the continental ice sheets are not as simply interpreted as the data in this illustrative case, but it is nevertheless possible to make a rough estimate of the earth's isostatic response from data such as the following.

It is of much interest to determine the limits within which inequalities of load can be sustained by the earth's crust without adjustment by bending or faulting, and the Gaspé region may be considered from this point of view. A belt of mountains 50 miles long by about 12 miles wide was scarcely at all ice covered, and over double that length and breadth there appear to have been only small glaciers and ice sheets, while in the valleys to the south and north there was a thickness of from 1,250 to 2,300 feet. If there was perfect adjustment to the relief from load, the borders of the peninsula should have risen from 400 to 800 feet while the mountain axis remained at its old level. . . .

The excellent grading of the rivers and the almost complete absence of lakes or flood plains where they enter the sea prove that the region rose as a

whole although the relief from load was almost confined to the north and south and amounted to little or nothing at the center.

One may draw the conclusion that the earth's crust can sustain inequalities of load amounting to 1,500 or 2,000 feet of ice, or the equivalent weight of rock, where the width of the region in question is not greater than 75 miles, the load decreasing from a maximum at the two sides to nothing in the center.

The lack of differential elevation in the Gaspé peninsula may be contrasted with the doming up of Newfoundland after the Ice Age, as indicated by Tyrrell and Fairchild. . . . .

Newfoundland has diameters of about 300 miles by 200, ... and it seems that a portion of the earth's crust of those dimensions does not change its level as a whole, but undergoes differential elevation to correspond to the varying relief from load; or, to put it another way, the earth's crust is not strong enough to resist isostatic adjustments where the area affected is 200 miles wide, but can support the difference of load where the width is only 75 miles.[1]

This evidence shows that a portion of the crust 200 miles wide can be warped by differential loading, but it does not determine exactly the minimum dimension of an independently balanced portion of the crust, because, on one hand, the whole of the warped portion may be wider than 200 miles, and on the other, it may be of this width merely because the load was an extensive one. But the minimum dimension is clearly greater than 75 miles. Accordingly, as an estimate, the limit may be placed at 200 miles, a figure which seems in general agreement with other evidence, such as the fact that the removal of small ice lobes caused no local warping.

The degree of balance of such an independently acting unit of the crust can be indicated as follows: The removal of the continental ice sheets, which formed a load probably equivalent to that of a layer of rock about a mile thick, was followed by uplift. This adjustment no doubt compensated a large part of the loss of mass, say four-fifths, as suggested by the success of using the hypothesis of perfect isostatic balance in glacial studies. Accordingly, an estimate is that the excess or deficiency of mass in an independently acting portion of the crust is less than one-fifth of a cubic mile of rock per square mile of area.

The conclusions that have been given may be summarized in the following working hypothesis of isostasy: The addition of a mass

[1] A. P. Coleman, "Extent and Thickness of the Labrador Ice Sheet," *Bull. Geol. Soc. America*, Vol. XXXI (1920), pp. 326–27.

greater than the equivalent of a layer or rock one-fifth of a mile thick over an area 200 miles wide would cause a depression approximately as wide as the load. If the load were concentrated, say as a layer of rock 2 miles thick over an area 20 miles wide, it would cause a depression extending about 100 miles on either side of the loaded area. As a corollary, if no addition of mass of effective amount is made to a portion of the crust, it will not move as a whole vertically, and any movement of its surface must be due to an expansion or contraction of this portion of the crust.

OTHER GEOLOGIC CONSIDERATIONS

A note may be added here to explain why the glacial evidence is given a commanding position in developing this working hypothesis of isostasy. The reason is that the records of the results of most horizontal transfers of mass in the crust are inconclusive, or may be objected to for one cause or another. To illustrate this point, the evidence of peneplanation may be considered. At first thought it would seem that an improbable amount of erosion would be necessary to base-level a mountain mass if isostatic adjustment were active, because the surface would rise almost as fast as it was eroded. This would be true if no other processes were active during the peneplanation. But the possibility that the crust was contracting during this period cannot be dismissed. In fact, such contraction seems quite probable. Relaxational movements following times of great crustal shortening have been noted, and may be considered as the natural reversal of such processes as the heating which accompanies mountain building. Such contraction, then, may reduce to reasonable figures the amount of erosion necessary for peneplanation, even though isostatic adjustment takes place during the erosional period. The general objection, then, to the use of records of erosion and deposition as tests of the theory of isostasy is that these processes are so localized with respect to earth structures that the action of other processes modifying the simple relationship between loading and depression or unloading and uplift cannot safely be eliminated. This objection cannot be reasonably used against the glacial evidence because the ice load was removed from such a variety of earth structures that the accompanying uplift can

hardly be thought of as due to some cause other than the unloading and only related by chance to this unloading.

THE GEODETIC EVIDENCE OF ISOSTASY

In brief, the geodetic evidence of isostasy is the fact that the direction and intensity of gravity can be calculated better on the basis of isostasy than on any other basis that has been employed. Before reviewing this evidence in detail, an outline of the nature of the calculations is given for the benefit of those who are unfamiliar with it.

THE GEODETIC CALCULATIONS

For simplicity, the earth is regarded as a sphere, instead of a spheroid of revolution, an assumption which does not vitiate the

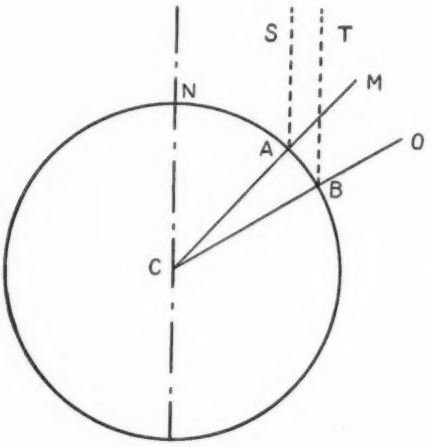

FIG. 1

explanation of the method of calculation. In Figure 1, C is the center of the earth, and N is the north pole. AS and BT are parallel to the earth's axis, and are determined for stations A and B by observations of the north star, which lies near the projection of the earth's axis at practically infinite distance. By observing the angle between AS and the vertical AM, and also that between BT and BO, the angle ACB can be determined. Then, knowing the size of the earth, it is possible to calculate the length of the arc AB. This

can also be determined by direct measurements on the surface. The two results should check if the plumb lines at the stations indicate truly the directions *AC* and *BC*. If they do not check, it is possible to determine the amounts of the deflections of the plumb lines.

From such measurements it was found that the plumb lines are deflected toward the mountains. Naturally, geodesists desired to calculate the deflections, and first tried the method of computing the deflections that would result by considering the mountain masses as adding their attractive forces to that of the smooth, homogeneous sphere imagined by their absence. But such a calculation gave too large a deflection. As the masses of the topographic features were determined with fair precision, the indication is that the smooth sphere is not of uniform density, but has subnormal densities beneath the mountains.

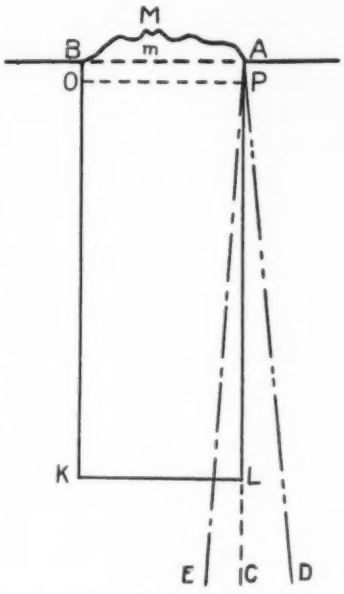

FIG. 2

This result suggested the use of the theory of isostasy as a basis for calculating the deflections, and in 1909 Hayford[1] published the results of his method of using this basis, which may be shown diagrammatically as follows: In Figure 2, *AC* is the line joining station *A* with the center of the earth. *AE* is the direction of the plumb line at *A*, and the problem is to calculate the deflection *EAC*. We have already noted that simply correcting for the attraction due to the mountain mass, *m*, gives a deflection that is too large, such as *EAD*. There is then assumed complete compensation, or a deficiency of mass equal to *m*, in the column below the mountain. If this were

[1] J. F. Hayford, *The Figure of the Earth and Isostasy from Measurements in the United States*, U.S. Coast and Geodetic Survey, 1909.

distributed in the portion *BOPA*, its effect would obviously nearly balance the attraction of the mountain mass, and the calculated deflection would be zero, or nearly zero. But, by distributing it uniformly through a column of greater length, the calculated deflection assumes some value between zero and *EAD*, and for a certain length of column, *BK*, it is equal to *EAC*. By calculations on this basis which included all topography and all stations, Hayford found that, using columns of a uniform length of about 72 miles, the computed deflections of the vertical agreed well with the observed deflections, the errors being reduced to 10 per cent of what they would be if figured on the basis that there is no compensation of mountain masses or ocean basins by deficiencies or excesses of mass in the crust below them.

Subsequently, a method based on the same density distribution was used to calculate the force of gravity.[1] As it is much easier to measure the force of gravity than the deflection of the vertical, the amount of information obtained from the gravity calculations is much greater than that obtained from the calculations of the deflections of the vertical.

The force of gravity is measured to the nearest one-thousandth of a dyne, which gives its value within about one part in a million. The difference between a measured and a calculated value is the gravity anomaly, which is called positive if the observed value is the greater. It is found that the anomalies which result from calculating the force of gravity on the basis of isostatic compensation are only from 10–15 per cent of what they would be if the force of gravity were calculated on the basis of no compensation.

Probably the clearest demonstration of the results of these calculations is that given by the anomaly maps. When the anomalies determined on the basis of no compensation are plotted by the contour method, the anomaly contours follow the general contours of the earth's surface. On the other hand, the plotting of the isostatic anomalies shows no relation to the topography. This is convincing testimony of the success attending the isostatic method of correcting for topography.

[1] William Bowie, *Special Publications 40 and 99*, U.S. Coast and Geodetic Survey.

DISCUSSION OF THE HYPOTHESIS USED IN THE CALCULATIONS

The foregoing outline shows that the geodetic method of calculating the direction and intensity of gravity is based on a hypothesis of isostasy that is not identical with the geologic hypothesis given in a preceding section of this paper. Accordingly, it might appear that the geodetic evidence on isostasy is opposed to the geologic evidence. However, the conflict is more apparent than real, as is shown by the following analysis of the geodetic method. For convenience, the hypothesis used by the geodesists is discussed under the headings of the various assumptions which compose this hypothesis.

1. The geodesists assume that compensation is local, that is, that the crustal column under a mountain is balanced against that under an adjacent valley. This assumption is not in accord with the geologic evidence. However, Bowie[1] and Putnam[2] have compared the anomalies computed on the basis of local compensation with those calculated on the assumption that the compensation extends horizontally 100 miles in all directions from a topographic feature, which is the mathematical statement of the concept that a portion of the crust 200 miles wide can act independently in isostatic adjustments. These comparisons show that the results are about the same in either case. Accordingly, the assumption of local compensation is permissible as a concession to the requirements of a mathematical treatment.

2. The calculations are based on the assumption of complete compensation. Although it is probable that the crustal balance is not perfect, the geologic evidence indicates a comparatively small excess or deficiency of mass for portions of the crust 200 miles wide or more, and accordingly this assumption can be accepted as a reasonable approximation of the facts.

3. To compute the amount of the compensation, sea-level is used as a datum plane. This method cannot lead to any appreciable error, as it is the relative densities of the columns that are used, and the absolute mass of each column is neither determinable nor necessary in the calculations. Quoting Bowie: "As a matter of fact,

[1] *Ibid.*, pp. 85–92.

[2] G. R. Putnam, *op. cit.*, pp. 301–2.

any equipotential surface of the earth or above it could be used as a datum for the computation of the effect of topography and isostatic compensation, but it is believed that the results would be the same as those obtained by the use of mean sea-level as the datum."[1]

4. In computing the compensation, geodesists also assume that the earth's crust from the level of the ocean deeps to that of the mountain tops has a uniform density. It is surprising that, after concluding that the density of the crust varies laterally, the geodesists did not then use the densities calculated for various parts of the crust instead of an average figure. But such higher approximations have in general been neglected, probably because it is found that the first approximation gives results that are within the practical limits of accuracy, and it is evident that the refinement suggested would have little effect on the calculations.

5. The compensation is distributed the same way in every column, so that its center of gravity is at the same depth in every column. This assumption neglects the natural irregularities in the earth's density distribution, a fact for which the geodesists have been obliged to make corrections in certain areas. For example, the gravity anomalies for stations on Cenozoic rocks tend to be strongly negative. The explanation given is that the columns under such areas are topped by layers of unconsolidated sediments of abnormally low density. As the attraction varies inversely with the square of the distance, the presence of this light material near a station has a pronounced effect. Thus, the mass of such columns is not considered to be deficient, but the large anomalies are ascribed to the effect of an abnormal distribution of mass. The effect, however, is local, and stations a short distance away are not influenced by it. It is therefore concluded that, although the local importance of abnormal density variations is evident, no large general error results from considering each column to be the same as another as far as the effect of its heterogeneity is concerned. In other words, the assumption that the center of gravity of the compensation is at the same depth in every column is a reasonable first approximation.

[1] William Bowie, *Isostasy*, p. 56. New York: Dutton & Co., 1927.

6. The geodesists assume that the compensation is distributed uniformly with depth. This assumption, however, is not essential, as Bowie[1] has pointed out that any distribution may be used without affecting the results as long as the center of gravity of the compensation is assumed to be about 25 miles below sea-level. Thus the restrictions as to the depth of compensation are removed, because, by postulating a compensation decreasing with depth, the figure for the depth of compensation may be increased to 150 miles or more, provided the compensation is distributed so that its center of gravity is at a depth of 25 miles.

7. A uniform depth of the crust is assumed. Absolute uniformity, however, is not essential. Especially if the compensation is assumed to decrease with depth, a certain amount of variation in the depth of compensation would have little effect on the results, because the lateral variation of density at the base of the crust would be zero, that is, the same as that assumed for the subcrustal material.

8. The presence of a plastic zone below the crust which yields to long-continued differential stresses of relatively small intensity is assumed, as in any hypothesis of isostasy. The evidence of vertical movements of the crust due to changes in its mass indicates the existence of such a zone. In addition, the following theoretical views support this assumption.

Barrell,[2] after an exhaustive survey of various kinds of data, concludes that there is a deep zone, which he calls the asthenosphere, in which "flowage is conceived as taking place with but little expenditure of energy by a ready recrystallization at the temperature of primary crystallization of magmas."

Willis,[3] from an analysis based largely on Adams' experiments with rocks under confining pressures, arrives at essentially the same conclusion.

Winchell[4] has extrapolated the data on the earth's temperature

[1] *Ibid.*, p. 58.

[2] Joseph Barrell, "The Strength of the Earth's Crust," Part VIII, *Jour. Geol.*, Vol. XXIII (1915), pp. 425–43, 499–515.

[3] Bailey Willis, "Discoidal Structure of the Lithosphere," *Bull. Geol. Soc. America*, Vol. XXXI (1920), pp. 247–302.

[4] A. N. Winchell, personal communication.

gradient and the crystallization temperature of rocks to indicate a deep zone where the best conditions for the formation of magmas exist.

9. The gravitative attraction of the part of the earth below the crust is assumed to be that of a homogeneous body or one composed of concentric shells, each uniform in density. Willis[1] has objected to the implication that the central part of the earth is homogeneous, but believes that the effects of its heterogeneity are negligible, so that, as far as the calculations are concerned, it can be considered as homogeneous.

The conclusion drawn from this analysis of the method of calculating the direction and intensity of gravity, and from the fact that it yields results that are very satisfactory when compared with the observed data, is that the geodetic work is a confirmatory test of the geologic hypothesis of isostasy. However, the value of this test is left somewhat in doubt by the fact that one of the assumptions is chosen so as to give the minimum error. This assumption concerns the depth of the center of gravity of the compensation, which is taken as about 25 miles because this figure gives the best results. Thus, in the absence of independent evidence as to this depth, the calculations may be looked on as a means of defining it, rather than as a check on the geologic theory of isostasy, to which the other assumptions are the equivalent. However, as the figure used for the depth to the center of gravity of the compensations seems reasonable, the writer is inclined to accept the geodetic calculations as lending some support to the theory of isostasy.

CONCERNING THE PROOF OF ISOSTASY

On the foregoing pages there is a statement of a working hypothesis of isostasy which was deduced from geologic evidence concerning the movements which followed the unloading of certain portions of the crust. Later, it was concluded that the geodetic calculations of the direction and intensity of gravity support this hypothesis. The reader may already agree that the proof of this hypothesis is the geologic evidence, and not the geodetic calculations, but, as there is a common tendency to regard the geodetic calculations as

[1] *Op. cit.*, p. 273.

the proof of isostasy, the specific reasons behind the viewpoint advanced here will be taken up in detail.

THE GEODETIC DATA ALONE DO NOT PROVE ISOSTASY

MacMillan makes the following useful statement: "From a purely mathematical point of view, any set of a finite number of observations of the intensity and direction of gravity can be satisfied, not approximately, but exactly, in infinitely many ways by a proper distribution of density in the earth."[1] For example, the geodetic data could be satisfied by calculations based on the assumption of caverns in the mountains, and such an assumption would no doubt have been considered sound in the days when subterranean cavities played a large part in geologic hypotheses.

Stated in these words, this alternative now sounds absurd, but it is to be noted that a more or less equivalent concept can be expressed in terms of modern geologic thought. Thus Leith[2] presents the following argument. Uplift by tangential shortening disturbs an original isostatic condition, but, at the same time, initiates the processes of erosion and sedimentation, which tend to restore the isostatic condition. Also the intrusions which often accompany deformation bring light granitic rocks into the mountainous areas, and katamorphic processes, possibly aided by heat generated by the movements, tend to reduce the density of the uplifted portions. Thus the lower density of the rocks would affect the observations at nearby stations, and cause the general relation that is found between the geodetic data and topography.

In short, it is suggested by Leith that the geodetic data might be satisfied by calculations based on an immobile crustal structure and on a density distribution inferred from the known tendencies of certain processes set in action by mountain building. This is no doubt true, and such a solution would be one of the infinite number that satisfy the geodetic data.

Keeping MacMillan's statement clearly in mind serves the useful purpose of avoiding certain possible misunderstanding. For ex-

[1] W. D. MacMillan, "On the Hypothesis of Isostasy," *Jour. Geol.*, Vol. XXIV (1917), p. 111.

[2] C. K. Leith, *Structural Geology*, pp. 323–46. New York: Henry Holt & Co., 1923.

ample, if one accepts the geodetic data as the proof of isostasy, Leith's argument might be thought to remove this proof. But the choice of the most probable of the infinite solutions to the geodetic data must clearly be based on evidence other than the geodetic data, such as the geologic evidence of isostatic adjustment. In short, the demonstration of the existence of isostatic adjustment is independent of the geodetic calculations.

In passing, it may be noted that all the processes mentioned by Leith can work just as well in conjunction with isostatic adjustment as not. That is, such processes are of interest in analyzing the origin, rather than the degree of balance, of the density distribution of the crust. For example, they may be used in studying the cause of the subnormal density of the continental portions of the crust. It will probably be granted that movement has been concentrated in these portions, and it seems reasonable that the processes attending the movements helped to cause their lower density. To illustrate, it has been calculated that katamorphism produces 111 cubic centimeters of sediments from 100 cubic centimeters of average igneous rock, and that 72,000,000 cubic miles of igneous rock have been weathered and the material redistributed as sediments.[1] The corresponding volume increase is equal to the volume of a layer 700 feet thick over the continental areas.

THE GEODETIC DATA CANNOT BE USED TO DEFINE A HYPOTHESIS OF ISOSTASY

Although admitting that the geodetic data alone do not prove isostasy as a general theory, many geodesists and geologists appear to believe that the data can be employed to define certain of the assumptions used in the calculations. For example, the statement is made that the geodetic data show that a crustal column cannot have more than a certain specified excess of mass. Such statements, however, are not sound, as may be shown by an analysis of the geodetic method of calculation.

The geodetic method of calculation requires a certain number of assumptions concerning the density distribution of the earth in order to compute the direction and intensity of gravity. All of these

[1] C. K. Leith and W. J. Mead, *Metamorphic Geology*, 1915.

assumptions but one are defined independently, as practical approximations either of the known facts or of the postulates of the geologic hypothesis of isostasy. The remaining assumption, which concerns the depth to the center of gravity of the compensation, is then defined by using the geodetic measurements of the direction and intensity of gravity, that depth being used which gives the best agreement between the calculated and the measured values of gravity. Thus the geodetic data constitute the independent evidence introduced to define the remaining assumption. So far the reasoning is sound. But when the assumption so defined is next used, together with the same geodetic data, to redefine one of the assumptions previously accepted as a practical approximation of one of the postulates of the geologic hypothesis of isostasy, the reasoning is no longer sound.

This argument is the basis of the objection to a geodetic definition of isostasy, but it may be more convincing to the reader to give an example showing the inability of the calculations to define isostasy. One of the questions that a hypothesis of isostasy should answer is: How great an excess of mass may there be present in a crustal column? Let us find out whether the geodetic data can be used to answer this question. In one series of calculations the effect of assuming incomplete compensation is tested. It is found that, if discs of rock 3,000 feet thick and 36 miles in diameter are considered to be uncompensated, the calculated intensities of gravity are very discordant with the observed intensities. Therefore it is concluded that the excess of mass that may be present in a crustal column 36 miles in diameter is much less than the mass of a layer of rock 3,000 feet thick.[1] In another series of calculations the effect of assuming regional compensation is tested. The conclusion reached is that the compensation for a topographic feature may be distributed 37–104 miles in all directions from it.[2] This means that, if a layer of rock 3,000 feet thick were placed on a crustal column 36 miles in diameter, isostatic adjustment might leave an excess of mass in this column nearly equal to the mass of a layer of

[1] William Bowie, *Isostasy*, p. 105.

[2] William Bowie, *Special Publication 40*, U.S. Coast and Geodetic Survey, pp. 85–92.

rock 3,000 feet thick, because only part of the compensation would be distributed in this column, the rest being in the crust surrounding the column to a distance of 37–104 miles in all directions horizontally. Thus these two sets of calculations lead to different conclusions: one, that the excess of mass that may be present in a crustal column 36 miles in diameter is much less than the mass of a layer of rock 3,000 feet thick, and the other, that this excess of mass may nearly equal that of a layer of rock 3,000 feet thick. Which of the two conclusions is more likely to be correct is clearly not determined by the geodetic calculations.

The conclusion reached here must not be taken to mean that the geodetic work has not been of great service in the study of isostasy. On the contrary, the mathematical statement of a hypothesis of isostasy has done much to give precision to our concepts of isostasy, and has suggested the way in which geologic evidence can be used to formulate a working hypothesis of isostasy. In addition, the calculations give, within certain limits of error, the depth to the center of gravity of compensation, which is a distinct contribution to our knowledge of the isostatic balance of the crust. This result, combined with evidence concerning the vertical distribution of compensation, could be used to estimate the thickness of the crust. The figure of 60 miles for this thickness, as an example, is based on the assumption that the distribution of compensation is uniform vertically.

In this connection, it appears that better co-operation between geologists is possible and would lead to mutual benefits. The part of the geologists in this work is to attempt to formulate better statements of the assumptions found necessary in the calculations. To the writer, it seems that the largest source of error lies in the neglect of the local irregularities in the density of the earth. These could be corrected for if geologists familiar with the structure would supply data on the density distribution of the portions of the crust near the stations where gravity is measured. In addition, instead of an average density of 2.67, it is suggested that the densities determined by Washington[1] be used for the portions of the crust that lie be-

[1] H. S. Washington, "Isostasy and Rock Density" *Bull. Geol. Soc. America*, Vol. XXXIII (1922), pp. 375–410.

tween the level of the highest peaks and that of the greatest ocean depths, and are situated some distance from the gravity stations.

CONCLUSIONS ON ISOSTASY

The geologic evidence suggests the following working hypothesis of isostasy. The addition to a portion of the earth's crust 200 miles wide, or more, of a load of rock more than one-fifth of a mile thick over the whole area would cause a depression which would restore the equilibrium to such a degree that the portion would have an excess of mass of one-fifth of a cubic mile of rock or less per square mile. The load might, or might not, cover a width of 200 miles. If it did not, the depression would nevertheless affect a portion of the crust at least 200 miles wide, because portions of such size seem to be the smallest ones that can act independently in isostatic adjustments.

This hypothesis also means that, if no addition of mass of effective amount were made to a portion of the earth's crust, it would not move as a whole vertically, and any vertical movement of its surface would be due to an expansion or contraction of this portion of the crust.

The geodetic calculations support this hypothesis in a comprehensive way, but they cannot be considered to prove the general theory of isostasy, nor to define a working hypothesis of isostasy.

THE APPLICATION OF ISOSTASY TO THE STUDY OF FOLDED MOUNTAINS

PRELIMINARY STATEMENT

Two aspects of the application of isostasy to the study of the origin of folded mountains will be discussed. One concerns the question of whether or not the theory of iostasy is in conflict with the geologic belief that the deformation recorded in mountain structures is due to regional compressive forces in the crust. The other concerns the cause of the high elevation of mountain ranges.

CONCERNING THE EXISTENCE OF REGIONAL COMPRESSIVE FORCES

Most geologists, viewing the record of the great tangential shortening in mountain building, believe that the deformation represents

the collapse of portions of the earth's crust, weakened by excessive sedimentation, under the action of regional compressive forces in the crust. But Bowie believes that the shortening is due, not to regional compressive forces, but to horizontal forces developed incidentally in the vertical movement caused by the expansion of the portion of the crust under the mountainous region. A review and discussion of his main arguments follow.

Bowie[1] believes that none of the theories advanced to account for the existence of regional compressive stresses in the earth is probable. The inference is that therefore such forces do not exist. But this cannot be accepted, as there is considerable agreement among geologists that such forces are shown by the structural record, and this belief is not founded, nor dependent, on the presence of a theory to explain it.

Bowie writes:

> Areas of sedimentation from which the mountain masses are formed are found to be in isostatic equilibrium and mountain areas are also; therefore the forces which uplift mountains are not horizontal. If they were horizontal, there would be extra loads on the blocks of the isostatic shell, but the geodetic data furnish evidence that the mountains are not extra loads and therefore must be caused by vertical forces which bring extra material into the columns. These vertical forces expand the material of the original column sufficiently to change the elevation of the surface.[2]

This argument is clearly answered by Burrard:

> But a different form of conclusion has been drawn from the theory of isostasy, one which has not been based on geodetic observation. In company with other geodesists, I have myself in the past fortified my convictions by means of this very conclusion of which I am not so doubtful. It has been argued that the theory of isostasy excludes all hypotheses which give to mountains additional mass, and that therefore mountains cannot have originated from horizontal folding, because horizontal folding and compression imply additional mass pushed in from the sides.
>
> Of recent years geodetic observations have shown that however rock-mass may be moved about over the surface of the earth, the changes in its surface position become compensated at depth. If mass is eroded from a mountain peak, the loss from erosion becomes locally compensated, and if mass is deposited in alluvial beds, the additional load becomes compensated. . . . . If these

[1] William Bowie, *Isostasy*, pp. 200–246.

[2] William Bowie, *Special Publication 99*, U.S. Coast and Geodetic Survey, p. 40.

deltaic loads, brought in from one side, become automatically compensated, why should not loads which have been accumulated locally by folding be also compensated?[1]

Bowie's proposed substitute for a regional compressive force in the crust is the horizontal force developed incidentally by the expansion that caused the uplift of the mountains. Probably the main objection to this idea is the fact that uplift and folding do not show the simple relationship to one another that is required. For example, some uplifts, such as those shown by high plateaus of undeformed rocks, are not accompanied by folding. Another objection is that such calculations as have been made of this expansion show it to be inadequate to account for even the elevation of mountain ranges, and accordingly it does not seem reasonable to impose on the expansion the further task of being resolved into horizontal components of such magnitude as to cause the recorded tangential shortening. Bowie realizes this, but believes that the expansion is greater than the amount he has calculated. He writes: "If these changes in volume do not occur, then the isostatic principle is false."[2] The writer cannot agree with this inference, because the argument leaves out of consideration the fact that some of the uplift may be due to processes other than expansion, such as the change of the composition of the deformed crustal columns due to folding, which increases the proportion of the light upper crust in the deformed column.

To summarize this section, it is concluded that Bowie has not shown the absence of regional compressive forces in the crust, and that it is not possible to accept his proposed substitute, the horizontal forces developed incidentally in the expansion of the portion of the crust under the mountains.

THE CAUSE OF THE ELEVATION OF FOLDED MOUNTAIN RANGES

The structure of a great mountain range records that there was once a portion of the crust, with its surface near sea-level, which was deformed so as to be shortened in a horizontal direction, and

[1] "Folding of Mountain Ranges—the Argument from Isostasy," *Bull. Geol. Soc. America*, Vol. XXXIII (1922), p. 336.

[2] William Bowie, *Isostasy*, p. 252.

then was left with its surface considerably above sea-level as a mass whose uppermost part consisted of folded sedimentary rocks, together with, in most cases, intrusive granitic rocks. Now, according to the theory of isostasy, a portion of the crust with a high surface elevation has a smaller mean density than one with its surface at sea-level, and therefore the mountain building lowered the mean density of the deformed portion of the crust. This means that a theory of mountain building, to be consistent with the theory of isostasy, must include processes which bring about the required lowering of density. Some of the more important of these processes, which have been suggested by students of orogeny, or are implied by the common concepts of mountain building, are given below.

1. The tangential shortening due to the collapse of weak portions of the crust under horizontal regional compressive forces tends to telescope and thicken this portion of the crust. However, most of the thickening is lost, because isostatic adjustment causes depression, whereby the loss of the lower part of the thickened crust by its passage into the plastic zone keeps the mass of the crust about constant per unit of horizontal area. But, as the light surface rocks remain thickened in the top of the deformed portion, this has a larger proportion of light material than before, and its mean density is therefore decreased, so that its surface stands higher than before.

2. Lawson suggests that the regional compressive forces are stored as elastic energy and are released by the collapse of portions of the crust weakened by the formation of sedimentary troughs. The resulting elastic expansion would then reduce the density of the deformed zone and of the flanking portions of the crust. Thus there would be caused an uplift, not only of the mountain range, but also of the flat-lying sedimentary formations on either side to form plateaus sloping up toward the mountains.[1]

3. Bowie's[2] calculated uplift due to expansion is based on the idea that the heat flowing into a column that is depressed by sedimentation lags behind the depression, and then, after the loading and sinking cease, due to the building up of the surface, causes an

[1] A. C. Lawson, "Folded Mountains and Isostasy," *Bull. Geol. Soc. America*, Vol. XXXVIII (1927), pp. 263–74.

[2] William Bowie, *Isostasy*, p. 251.

expansion of the column. Another source of heat for the column is that which is generated by the deformation, assuming that this is the result of a release of energy stored in the crust as compressive forces. This heat might stop or even reverse the flow suggested by Bowie. In the latter case the heat would tend to be lost from the column, but, as heat is conducted very slowly by rocks, the thermal expansion might be localized in the deformed region for a time that is long even when measured by geologic standards.

4. The igneous activity that accompanies deformation is evidence of liquefaction of portions of the deformed crust. This process involves an increase of volume, which, however, is largely lost when the magma consolidates. But there may be some slight gain in volume, due to differentiation, which because it breaks up complex atomic or molecular structures into simpler components, that is, consists essentially of unmixing, may from general considerations be supposed to result in an increase in volume. Accordingly, the consolidation of a magma as a series of differentiates may result in a solid product of larger volume than the solid material from which the magma originated.

CONCLUSIONS CONCERNING THE APPLICATION OF ISOSTASY TO THE STUDY OF THE FOLDED MOUNTAINS

It is concluded that the theory of isostasy is not in conflict with the accepted belief that formation of folded mountain ranges is the result of a collapse of portions of the earth's crust under regional compressive stresses. On the contrary, the common concept of mountain building, built around this belief, involves processes which tend to reduce the mean density of the deformed portions of the crust, so that it is supported by the theory of isostasy. Before closing it may be well to note that this discussion deals only with folded mountains and the uplift that followed more or less directly after the folding. It does not refer to uplifts of undeformed strata or of peneplained regions of folded strata.

SYNGENETIC PYRITIZATION IN LOCAL REDUCING AREAS OF PENNSYLVANIAN SHALES IN MISSOURI

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ABSTRACT

A black shale with pyritized fossils occurs just over the Bevier coal in Boone County, Missouri. This shale is local in occurrence, lenticular, and thin. An impervious gray shale with very little pyrite occurs above it, and locally an unpyritized fossiliferous gray shale occurs below. The pyritization is believed to be syngenetic. The conditions favorable to such an origin are believed to have been similar to those now found in limans.

A black, fossiliferous shale, local in extent, occurs in association with the Bevier coal (Pennsylvanian) in a number of places in Boone County, Missouri. The shale usually rests on the coal, but there may be from 15 to 20 inches of medium to dark gray shale between. The fossils in this black shale are almost completely pyritized, only exceptionally thick shells being not wholly altered. The pyritized shale is always thin (the maximum thickness so far noted was 12 inches) and lenticular, pinching out laterally. These lenticular beds are always short, the longest in any mine being about 200 feet, with a width that is somewhat less. No connection between adjacent areas of the shale has been observed, but this is probably due to the limited exposures in the mines, because the faunas of this pyritized shale are similar even in different mines.

In one mine the black, pyritized shale was underlain by a gray, fossiliferous, calcareous (but unpyritized) shale. This gray shale had a maximum thickness of ten inches, and, like the black shale, pinched out laterally. The rock immediately overlying the black shale is a light-gray thinly laminated shale. Locally, small elliptical pyrite nodules occur at the base of this shale, and, more rarely, one to two feet above the base. They are in no way connected with the pyritization of the black shale.

The pyritized fossils have their original details beautifully preserved, which indicates that pyritization occurred soon after the death of the organism and before normal disintegration destroyed these details. The original shells were for the most part very thin (a characteristic feature of the shells of organisms found in black shales), and as a result the pyrite pseudomorphs are thin. The thick shells may be partly replaced by a thin layer on the outer and inner sides of the shell, or, if the inner side was buried in mud, and therefore inaccessible, the pyrite occurs only on the upper exposed surface. The pyrite may be in layers on the shell, indicating that the conditions favorable for its deposition varied from time to time. The calcareous fossils in the shale below do not show such perfect preservation as the pyritized ones of the black shale, due to their having been more broken up before burial.

CONDITIONS OF DEPOSITION

This black shale, occurring adjacent to shales of such an entirely different character, must have been deposited under rather exceptional conditions. The pyritization is held to have occurred simultaneously with the deposition of the inclosing beds. The facts that a gray unpyritized shale with calcareous fossils immediately underlies this black shale, and that the overlying light-colored shale only contains pyrite locally, indicate that the conditions for pyritization were limited to the period of deposition of the black shale or soon after.

The lenticular shape and small size of the beds of black shale point to the existence of local depressions on the floor of the sea, in which there was no movement or aeration of the water. The forms are marine, hence the sea had submerged the coal swamp in which the Bevier coal had been deposited. The fauna of the black shale consists largely of pelecypods, with some gastropods, brachiopods, and crinoids, and that of the gray shale below consists of fusulinas, some crinoids, and a sprinkling of other forms.

The conditions governing the deposition of both extensive and local deposits of black shales have been fully discussed by Androus-

sow,[1] Geikie,[2] Clarke,[3] Murray,[4] Schuchert,[5] Ruedemann,[6] Ulrich,[7] Twenhofel,[8] and others. The features regarded as characteristic of such black shales, and emphasized by these authors, are found in greater or less degree in the shale discussed in this paper. The areal distribution of the beds, their lenticular character, the continuous horizontal beds overlying them, and the depressions in the coal bed, all prove unmistakably that the shale was formed in local depressions in what was probably a shallow sea, the first one to submerge the swamp after the coal was deposited. The abundance of sulphides proves that the water in these depressions was reducing in character, for most of the foregoing authors note that wherever black muds are now accumulating, hydrogen sulphide is common, that the muds often contain ferrous sulphide and less often sulphur, and that the shells of organisms in them are usually thin and sometimes pyritized.

The sequence of events in the pyritization of the fossils has been difficult to work out and is probably not so simple as the reactions given below suggest. In fact, there are some points upon which more information must be sought. The points which this paper attempts to explain are: (1) the source of the sulphur, whatever its combining form, (2) the source of the iron, and (3) the method of replacing the calcareous shell.

1. The source of the sulphur is most likely to be found in the action of certain bacteria. There are two classes of anaerobic, putrefying, and reducing bacteria found in black muds[9] that might, and probably did, contribute the hydrogen sulphide to the water.

[1] N. Androussow, *Guide to the Excursions of the Seventh Internat. Geol. Congress* (1897), pp. 6, 27, etc.

[2] A. Geikie, *Textbook of Geology*, Vol. I (1903), p. 582.

[3] J. M. Clarke, *New York State Museum Bull. 6* (1913), pp. 199–201.

[4] Sir John Murray, *The Depths of the Ocean*, pp. 175, 181, 182, 187, 188, 257, 554.

[5] Charles Schuchert, *Popular Science Monthly* (June, 1910), p. 598.

[6] R. Ruedemann, *Bull. Geol. Soc. Amer.*, Vol. XXII (1911), p. 234.

[7] E. O. Ulrich, *ibid.*, p. 358.

[8] W. H. Twenhofel, *Amer. Jour. Science*, Vol. XL (1915), p. 272. W. H. Twenhofel and others, *Treatise on Sedimentation* (1926), p. 199.

[9] E. C. Harder, *U.S. Geol. Survey Prof. Paper 113*, p. 82. See also F. W. Clarke, "The Data of Geochemistry," *Bull. U.S. Geol. Survey 770, 150, 518*, and the papers cited above.

(*a*) All putrefying bacteria liberate hydrogen sulphide from the sulphur-bearing proteins of decaying organisms. (*b*) The reducing bacteria are capable of breaking up sulphates, sulphites, or thiosulphates, using the oxygen so obtained to combine with carbon in their own life-processes and forming sulphides of the original salts. These sulphides, by reaction with carbon dioxide, may form hydrogen sulphide. There is a third group of bacteria that may occur with the foregoing groups as long as there is some oxygen available in the water. These bacteria oxidize hydrogen sulphide to free sulphur and sulphates. The first two groups of bacteria are especially active where there is a deficiency of oxygen, a condition that is met with in shallow depressions where there are no currents to aerate the waters. Here the oxygen supply soon becomes used up, and the hydrogen sulphide, formed from the decaying organic matter, remains unoxidized.

Under special conditions this third group may contribute free sulphur to the muds, but when the oxygen is gone at the bottom they move to a higher layer in the water where oxygen is still available. The formation of hydrogen sulphide by the putrefying bacteria would produce conditions favorable for the development of sulphur-freeing bacteria as long as some oxygen was available. With a deficiency in oxygen, the sulphate-reducing bacteria would become active and contribute to the formation of hydrogen sulphide. The hydrogen-sulphide-forming and sulphate-reducing bacteria are especially common in black muds, and in addition the oxidizing group may be present. The bacteria would appear to be an adequate source of the sulphur.

2. The iron was probably present in the water in the form of ferrous carbonate, as the abundance of vegetation on the land would favor its removal in solution. The widespread sideritic ores in the Pennsylvanian support this view. Any deficiency of oxygen would prevent its oxidation and precipitation, and the abundance of carbon dioxide (due to the decay of organic matter and the reducing bacteria) would favor its accumulation in the water. This ferrous carbonate would react with the hydrogen sulphide thus: $FeCO_3+H_2S=FeS+H_2CO_3$.

The ferrous sulphide formed, a black gel-like precipitate, would

be converted into pyrite or marcasite (more likely pyrite, as the solution would probably be weakly and not strongly acid) by the addition of free sulphur, liberated by the sulphur bacteria. The fact that blue and black muds contain ferrous sulphide, and, although less often, free sulphur, favors this theory as the initial step in producing the disulphide.

However, it is very probable that if the water were alkaline, the iron disulphide gel, melnikovite (also black like the ferrous sulphide), might be precipitated directly. As a gel, it is in a labile state and readily becomes the crystalline pyrite (or more rarely marcasite). It is of course also possible that the reducing bacteria would reduce ferrous sulphate, if any were present, to the sulphide, but the sulphate is not as probable a source as the carbonate.

3. The next and last step is the replacement of the shell. The preservation of the details of an organism proves that the substitution was a molecular one. The first deposition of iron sulphide was probably on the exposed surface of a shell. The decay of the organism would account for a greater abundance of hydrogen sulphide in the immediate vicinity of its shell. If precipitation was initiated elsewhere than on a shell, a nodule resulted. The reaction given before liberated carbon dioxide, whose presence would favor the solution of the calcium carbonate (which might be either calcite or aragonite) of the shell.

As the first deposited sulphide was on the surface, the replacement of the shell beneath would depend upon the diffusion inward of the iron disulphide, upon the formation of carbon dioxide by the reaction of the hydrogen sulphide with the ferrous carbonate, and the removal of the calcium carbonate. That the replacement depended upon the removal of the calcium carbonate is shown by the progressive pyritization inward. Both carbon dioxide and hydrogen sulphide, as gases, could diffuse inward, and it was also necessary that the ferrous carbonate do likewise. Decay of the thin organic tissues around the prisms or plates of calcium carbonate in the shell would further the entire series of reactions and may very probably be a more important factor in all replacements of shells than has been thought heretofore.

SUMMARY

The lenticular character of these beds, the nearly complete pyritization of all fossils in them, when considered in connection with their position between an unpyritized fossiliferous member below and a very impervious shale above, are taken to mean that the pyritization was syngenetic. The chemical conditions existing in modern limans would explain the origin of these pyritized shales in the Pennsylvanian very satisfactorily. Reducing conditions exist in these limans and bacteria that liberate hydrogen sulphide and sulphur are common. These products, freed especially near decaying organisms, induce precipitation and replacement of the shell by iron sulphide.

SYNGENETIC ORIGIN OF PYRITE CONCRETIONS IN THE PENNSYLVANIAN SHALES OF NORTH-CENTRAL MISSOURI

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ABSTRACT

Pyrite concretions are common in the Pennsylvanian shales immediately overlying the Bevier coal bed in north-central Missouri. They were studied in place in the shale and also with the microscope in the laboratory. A detailed account of their occurrence is given. The concretions are believed to be syngenetic in origin. This view is based upon the occurrence of the concretions, the possible conditions favorable for their formation which are believed to have existed in the Pennsylvanian seas, and corroborative evidence as furnished by the formation of pyrite in present-day seas.

INTRODUCTION

Many references concerning pyrite concretions occurring in coal and shales have been made in geologic literature. They have been called "sulphur balls" and "coal balls," but more often are referred to by miners as the "sulphur" or "brass" in the coal or shale. But they have not been described in detail; nor have their relationships to their inclosing beds been discussed. The concretions of chief concern in this paper were studied in place in the shales that overlie the coal in various mines in Boone, Callaway, and Randolph counties, Missouri. The relationships of the concretions to the inclosing beds and to each other were studied in detail. The concretions were also examined under the microscope for evidences of replacement and internal structures.

Thanks are due Dr. W. A. Tarr for kind criticism and helpful suggestions.

DESCRIPTION OF THE CONCRETIONS

Most of the concretions are composed of pyrite, and their surfaces are occasionally covered with small crystals. A few of the concretions examined give a characteristic reaction for marcasite in nitric acid when tested against known samples of pyrite. However,

no distinction is made between pyrite and marcasite in this paper. The interiors of the concretions are finely crystalline and dense, broken usually by a few irregular cracks and cavities which are often lined with small crystals. The cracks extend to the surface of the concretions and may be filled with gypsum and calcite, or with gypsum alone. The individual concretions are small, averaging from $\frac{1}{4}$ to one inch in thickness and from 1 to 4 inches in diameter. They are mostly irregular in horizontal sections, but in vertical sections a greater number of them may be described as ellipsoidal. All gradations from discoidal to roughly spherical forms exist. The concretions usually occur separately, but a number may coalesce to form a definite layer of pyrite which may be several feet in extent.

OCCURRENCE OF THE CONCRETIONS

INCLOSING BED OF SHALE

The inclosing rock in which the concretions occur is a shale of marine origin (on the average about 4 feet in thickness) and lies immediately above the Bevier coal bed. It is a member of the Cherokee formation of Pennsylvanian age and is very compact, fine-grained, and finely laminated. The color varies from a black at the contact with the coal to a light gray as the distance above the coal increases. In places there is a distinct change of color from black to gray. Where this was noticed, the dark-colored shale or individual layer contained numerous pyrite concretions, pyritized fossils, and disseminated grains of pyrite. The overlying light-colored shale contains a few concretions but no pyritized fossils. The dark-colored layers mentioned above rest immediately upon the coal and are thin and lenticular, the lenses not exceeding 300 feet in diameter.[1] The concretions in the dark-colored shale are larger and more numerous at or near the contact with the overlying light-colored shale. The fading out or sudden change from dark to light color is due to a decrease in the amount of carbonaceous matter contained in the shale.

RELATIONSHIP TO LAMINATIONS, JOINTS, AND FAULTS

Most of the concretions are distributed along definite planes paralleling the laminations in the shale. A few of them are vertically

[1] Personal communication with W. A. Tarr.

elongated and extend across the laminations, but their initial growth always started from a lamination plane.

The concretions rest in a shallow cup below which the laminations may or may not be slightly bent downward. The laminations that go over the tops of the concretions are decidedly bent upward, the degree of bending depending upon the size and shape of the concretions. The laminations continue over the tops and along the sides of the concretions without disruption, finally becoming horizontal again a short distance from the concretions.

A few joints cut the shale, but there is no apparent relationship between them and the concretions. Several faults of small displacement also cut the shale. Originally continuous layers of concretions have been offset by these faults, which is evidence that the faulting took place subsequent to the formation of the concretions. No pyrite occurs along the joints or fault planes, and there is no evidence that water has migrated along these planes.

DEVELOPMENT OF SLICKENSIDES

Slickensides are well developed on the tops and sides of the concretions. In some specimens they are also developed, though poorly, beneath the concretions. The slickensides are very smooth and curve to conform to the shapes of the concretions. The laminations in the shale above and below the concretions are not affected by these slickensides, the slickensides being confined to the actual surfaces of the concretions. Slickensides are also developed over the tops and sides of the fossils found in the shale along with the concretions.

RELATIONSHIP OF CONCRETIONS AND PYRITIZED FOSSILS

Commonly occurring in the shale with the concretions are numerous fossils, including brachiopods, bryozoans, gastropods, crinoid stems, and plant remains. The shells of a majority of these fossils are completely pyritized, but a few are only partially replaced by pyrite. A few of the shells still retain their original composition. The shells when pyritized, except for being broken, are extremely well preserved, the minutest details, such as plications on the shells and pinnules on the plants, being readily distinguishable. Most of the shells are crushed and, in many instances, the opposite valves

of the brachiopods are flattened out and in contact with one another. The pyritized shells occur in the dark-colored shales immediately above the coal. No fossils were found in any of the concretions.

ORIGIN OF THE CONCRETIONS

Concretions are classified as of either syngenetic or epigenetic origin, according to their age relative to the inclosing bed.[1] Those that are deposited at the same time, or immediately after deposition of the inclosing bed, are of syngenetic origin. They antedate the deposition of the overlying beds. Concretions that are of epigenetic origin have been formed later or subsequent to the deposition of the inclosing bed, and hence are younger than the beds that contain them.

SIGNIFICANCE OF THE INCLOSING ROCK

The character of the inclosing rock, a shale, is not favorable to the epigenetic origin of the concretions. Shale is an impervious rock, as shown by its common occurrence as a capping rock for artesian water and for oil and gas reservoirs. The openings in a shale are subcapillary in size, and hence are of little aid in the circulation of solutions. In the formation of epigenetic concretions the free movement of solutions is necessary in order to aggregate the disseminated mineral matter into concretions. If the adjacent beds, and especially the inclosing rock, are impermeable, then solutions cannot move through them and the concretions cannot be of epigenetic origin. It was also noted that only the concretions exposed show evidence of oxidation. This fact suggests that solutions do not move through the shale, or most of the concretions would have suffered some oxidation. The shale does not contain any replaceable material, and an examination of numerous polished sections of the concretions did not reveal any remains of material which may have been replaced by the pyrite.

SIGNIFICANCE OF THE OCCURRENCE OF THE CONCRETIONS

The persistency of the concretions occurring in definite planes between and parallel with the laminations in the shales points toward

[1] W. A. Tarr, *Treatise on Sedimentation*, compiled by W. H. Twenhofel (Baltimore, Maryland: Williams and Wilkins Co., 1926), p. 506.

their syngenetic origin. These concretions were probably formed on the bottom of a sea or basin, and thus any group of concretions precipitated at any one time would be deposited in the same plane. There is the possibility that solutions migrated along the bedding planes, and, if so, the concretions could be epigenetic in origin and distributed along definite planes. The writer is of the opinion that in the shale studied, solutions could have moved through any part of the shale as easily as along the bedding planes. Thus if the concretions were epigenetic in origin, they would probably occur disseminated through all parts of the inclosing bed, and a definite arrangement, as along planes, would be lacking.

A few of the concretions, as already stated, are of a greater vertical thickness than horizontal width. These concretions appear to have started growth in the normal way, but continued growing upward as the inclosing bed of shale was being deposited around them. Their upward growth was probably finally stopped, due to a depletion of material in solution, or by the concretions being completely covered with sediments. The laminations of the inclosing shale that come in contact with the sides of these concretions are slightly bent upward. This upward bending is probably the result of original deposition of shale around the concretion or of a slight movement of shale downward around the concretion during consolidation. It is believed that if the concretions were epigenetic in origin, there would be a more pronounced bending of the laminations or a crumpling in the surrounding shale due to the concretions pushing the shale aside during growth.

The relationship between concretions and the laminations of the inclosing beds has been variously interpreted. If the degree of curvature of the laminations above and below a concretion is approximately equal, and the laminations are crumpled along the sides of the concretion, the concretions are probably displacive or epigenetic in origin, as suggested by W. A. Tarr:

> Concretions growing by displacement should displace beds of like material uniformly above and below unless shallowly buried. Likewise, if growth proceeds in all directions, the beds at the sides of the concretions should show crumpling or thickening as a result of the lateral crowding.[1]

[1] *Ibid.*, p. 512.

If the concretions were formed at a considerable depth below the surface, room for them would have to be made by local compression of the shale as the concretions grew in size. Under such conditions the bending of the laminations above and below would be approximately the same. There might be a slight difference, as it is possible that upward yielding of the shale would still be easier than downward yielding.

The bending of laminations is most pronounced over the tops and sides of the concretions studied. They usually rest in shallow cups or depressions, these depressions being due probably to the material making up the concretions pressing down in the soft shale soon after its formation. Subsequent downward pressing during consolidation of the shale may also be a factor in the slight downward bend of the laminae noted in places. The fact that the same degree of bending is not common below and above the concretions, and that there is no evidence of crumpling of the laminations at the sides of the concretions, indicates that they are syngenetic in origin.

Further evidence that the concretions were syngenetic in origin was found in the similar bending of laminae over the tops and sides of the fossils found in the shale.

The absence of pyrite along the joints and fault planes in the shale is further evidence in support of the syngenetic origin of the concretions. The concretions were at least formed before the joints and faults, otherwise pyrite would be found along these openings, as they are channel ways along which water can migrate. The presence of some pyrite along the joints and fault planes would not prove, however, that the concretions were not deposited earlier, for there may have been two periods of deposition entirely independent of each other. The pyrite occurring along the other divisional openings could have been formed at a later date and be epigenetic in origin.

SIGNIFICANCE OF THE SLICKENSIDES

The occurrence of slickensides, which are highly developed on the sides and tops of the concretions and poorly developed on the bottoms, are open to several interpretations, as suggested by W. A. Tarr:

> If considered alone, they could be due to the beds being pushed up by growth or to the beds slipping down around the concretion. When studied in

connection with the arching of the beds and the lack of lines of stratification passing through the concretion, they are taken to mean that the beds, during consolidation, settled down around the concretion.[1]

It is believed that the slickensides are due to the shale slipping down around the concretion during the final stages of consolidation. The slickensides are best developed on the tops and sides of the concretions because it is there that the greatest amount of movement took place. The fact that slickensides are poorly developed, if present at all, beneath the concretions is indicative that little or no movement took place beneath them. Slickensides are also developed over the fossils found in the shale. They resemble those developed over the concretions and are further evidence that they are a result of the shale moving down over a resistant body.

SIGNIFICANCE OF PYRITIZED FOSSILS

The splendid preservation of the minute details of the fossils, which have been partially or completely replaced by pyrite, is significant. Many authors have found fossils inclosed in concretions; and in every instance they have noted their unusual preservation, which was probably because the animal or plant fell into a soft gel or was inclosed in a concretion soon after its death. No fossils were found in the concretions studied, but it is reasonable to believe that the remarkable preservation of the fossils could result if the replacement occurred soon after the death of the organisms. It is to be noted that the few fossils present in the shale that have not been replaced are poorly preserved. The excellent preservation of the replaced fossils points indirectly to the syngenetic origin of the concretions, for the body of water in which the animals or plants were deposited must have contained the necessary materials for the replacement of the fossils as well as for the formation of the concretions. The fossils that have not been replaced were probably covered over with mud soon after sinking to the bottom.

CHEMICAL FACTORS IN DETERMINING ORIGIN

The physical factors involved in determining the origin of concretions have been discussed, but the origin is not complete without

[1] W. A. Tarr, "Syngenetic Origin of Concretions in Shale," *Bull. Geol. Soc. Amer.*, Vol. XXXII (1921), p. 380.

considering the chemical factors involved in their formation. We should consider the character of Pennsylvanian seas, the source of materials, and the cause of precipitation.

During the Pennsylvanian period there existed numerous lakes and more or less inclosed seas. The seas of this period advanced from the Gulf of Mexico across Arkansas, Oklahoma, and Kansas and entered Missouri north of Kansas City.[1] Sedimentation was rapid, keeping pace with submergence and gradually resulting in the formation of numerous swampy basins in which there sprang up a vigorous vegetable growth.[2]

G. C. Broadhead described the coal-forming regions as "a gentle undulating land surface, over which were lakes and vast swamps, beginning to support a rare and luxuriant vegetable growth, the forerunner of coal periods."[3]

These coal-forming areas were sinking areas; and, after an indefinite period of vegetable growth and accumulation, the waters became too deep for further growth and deposition of sediments began to take place. It was in these bodies of water that the shale and pyrite were deposited simultaneously.

The land areas during Pennsylvanian times being low lying and flat furnished conditions whereby chemical weathering predominated. As a result, streams and groundwater would carry a relatively large amount of mineral matter in solution. In support of the view that considerable iron was in solution in the Pennsylvanian seas are the extensive occurrences of pyrite in coal and shales of that age, as well as the siderite deposits in the Pennsylvanian rocks of Ohio and elsewhere.

Pyrite may be precipitated, according to prevalent views, by reduction of iron sulphate in solution by organic matter, by sulphate-reducing bacteria, and by the action of hydrogen sulphide on iron sulphates or carbonates in solution. Numerous authors suggest that pyrite is formed by the reducing action of organic matter on iron

[1] Henry Hinds, "Coal Deposits of Missouri," *Mo. Bureau Geol. and Mines*, Vol. IX (1912), p. 4.

[2] E. B. Branson, "Geology of Missouri," *Univ. of Mo. Bull.*, Vol. XIX, No. 15 (1918), p. 73.

[3] G. C. Broadhead, "Report on Boone County and the Ozark Uplift," *Geol. Survey of Mo.*, Vol. XII, Pt. III (1898), p. 398.

sulphate in solution. No experimental evidence that pyrite can be formed in this manner has been given, the authors probably basing their opinions on the common association of pyrite in rocks with organic matter. Other authors[1] have shown by experiment that organic matter will not reduce iron sulphate to pyrite or the iron disulphide.

The second means of producing sulphides is by the action of sulphate-reducing bacteria, which remove the oxygen from the sulphates in solution, causing the direct precipitation of the sulphide.[2] Several bacteria have been described as having the power of reducing sulphates; but at the same time considerable quantities of hydrogen sulphide are usually liberated,[3] and it is probable that this gas causes the precipitation of the sulphides.

The third means of producing sulphides is by the action of hydrogen sulphide on sulphates and carbonates of the various metals. Hydrogen sulphide may be formed (1) by the decomposition of sulphur-bearing proteins in organic matter due to the action of various decay-producing bacteria, (2) by certain bacteria in the presence of organic matter acting directly upon free sulphur,[4] and (3) by the action of sulphate-reducing bacteria on sulphates in solution under anaerobic conditions.[5] This hydrogen sulphide would react with any iron in solution in the swamp water, and pyrite would be precipitated.

Hydrogen sulphide was probably plentiful during the period of deposition of the shales in which the concretions occur. There was a plentiful supply of decaying organic matter, and this gas may have been formed by any one or a combination of the foregoing means of producing hydrogen sulphide. Ferrous sulphide would be precipitated immediately when sulphates or carbonates of iron came in con-

[1] E. T. Allen, J. L. Crenshaw, and John Johnson, "The Mineral Sulphides of Iron, with Crystallographic Study by Esper S. Larsen," *Amer. Jour. Sci.*, 4th Ser., Vol. XIII (March, 1912), pp. 171–73.

[2] E. C. Harder, "Iron Depositing Bacteria and Their Geologic Relations," *U.S. Geol. Survey, Prof. Paper 113* (1919), p. 30.

[3] *Ibid.*, p. 41.

[4] *Ibid.*

[5] W. M. Beyerinck, "Über Spirrulum desulfuricous als Ursache von Sulfat-Reduction," *Centralbatt für Bakteriologie*, Ser. II, Vol. I (1894), pp. 1–9, 104–14.

tact with the gas. This compound subsequently changes to iron disulphide.[1]

The fact that the concretions and disseminated grains of pyrite and pyritized fossils are more numerous in the dark-colored shale suggests that the conditions present at the time of deposition of this part of the shale were ideal for the precipitation of pyrite. Organic matter was plentiful, as shown by the dark color of the shale. Hydrogen sulphide might have been derived by any of the means previously suggested.

THE ORIGIN OF THE GYPSUM AND CALCITE

The presence of gypsum, alone or with calcite, filling the cracks and cavities in some of the concretions is difficult to explain. It is believed that these minerals were deposited soon after the formation of the concretion. These minerals may have been introduced into the cracks even after burial of the concretion, but before the complete consolidation of the inclosing shale. Of the two minerals, gypsum was deposited in the greater abundance and probably first. Any reaction which would account for their origin would probably be complicated. The Pennsylvanian seas undoubtedly contained H_2S, NH_4CO_3, NH_4OH, and S, due to the decomposition of the organic matter, besides the various salts of iron and calcium.

CORROBORATIVE EVIDENCE OF THE SYNGENETIC ORIGIN OF THE CONCRETIONS

C. E. Siebenthal,[2] in citing O. Stutzer, says:

> Hydrogen sulphide is plentiful in certain Russian lakes and seas which do not have an effective vertical circulation. In the water of Weissowo Salt Lake, for instance, there is thirty times as much hydrogen sulphide at a depth of 61.3 feet as at a depth of 52 feet. In the Black Sea there is about twenty times as much hydrogen sulphide at a depth of 800 feet as at a depth of 700 feet.

A. O. Hayes,[3] in citing H. Androwssow, says:

> He has found that a micro-organism, *Bacterium hydrosulfuricum poriticum*, liberates hydrogen sulphide not only from albuminoids, but also directly from

[1] W. H. Newhouse, "Some Forms of Iron Sulphide Occurring in Coal and Other Sedimentary Rocks," *Jour. of Geol.*, Vol. XXXV (1927), p. 80.

[2] C. E. Siebenthal, "Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma," *U.S. Geol. Survey, Bull. 606* (1915), p. 63.

[3] A. O. Hayes, "Wabana Iron Ore of Newfoundland," *Canada Dept. of Mines, Geol. Survey, Memoir 78*, No. 66, Geol. Ser. (1915), p. 90.

sulphates and sulphides, and ferrous sulphide results from the action of the hydrogen sulphide on iron salts. In depths of 300 to 717 fathoms two varieties of mud were found, a viscous sticky black mud holding iron sulphide (FeS), and a less dense blue mud holding plagic diatoms, a smaller quantity of FeS, and concretions of FeS_2. The blue mud is thought to underlie the black mud. Thus the fact is established that FeS_2 is produced in bottom deposits of the Black Sea at depths of 300 to 717 fathoms.

G. Forchammer describes the occurrence of pyrite on the western shore of Bornholm in the Baltic Sea: "All the rolled stones at the bottom of the sea are covered with a beautiful yellow metallic coating of iron pyrites."[1] The pyrite was precipitated by hydrogen sulphide derived from the decay of seaweeds, a gas which is abundant in this region, as shown by G. Forchammer: "In the neighborhood of Copenhagen, the disengagement of sulphuretted hydrogen from the sea weeds is sometimes so strong that the silver at the country places near the shore is constantly blackened by the effect of that gas."[2]

Iron sulphide also occurs in many other localities. The best known are the eastern Mediterranean Sea, Black Sea, Sea of Azov, Caspian Sea, Dead Sea, Aral Sea, and other inclosed bodies of water in Southeastern Europe and Western Asia. It also occurs in black muds around Oesel Island and elsewhere in the Gulf of Riga, at several localities in the southern Baltic Sea (one of which was described), around the mouths of the Elbe and Weser, and along the Netherlands Coast in the North Sea.[3]

SUMMARY

It is believed that the concretions studied are syngenetic in origin, i.e., deposited contemporaneously with the inclosing shale. The reasons for this conclusion are based upon (1) the occurrence of the concretions, (2) the chemical origin of the concretions, and (3) corroborative evidence afforded by the formation of pyrite in present-day bodies of water.

[1] G. Forchammer, "On the Influence of Fucoidal Plants upon the Formations of the Earth, on Metamorphism in General, and Particularly the Metamorphosis of the Scandinavian Alum Slate," *Report of 14th Meeting of Brit. Assoc. for Advancement of Sci.* (September, 1844), pp. 155–69.

[2] *Ibid.*, p. 160. [3] E. C. Harder, *op. cit.*, p. 63.

NATURAL BOUNDARIES IN THE INTERIOR LOW PLATEAU PHYSIOGRAPHIC PROVINCE[1]

RICHARD FOSTER FLINT

ABSTRACT

The portion of the Interior Low Plateau province which lies west of the Lexington plain and northwest of the Nashville Basin consists of two distinct and individual physiographic units, sharply separated from one another by the curving line of the Dripping Springs escarpment and its northward equivalent. The southeastern unit is a part of the Highland Rim section; the name "Shawnee Hills section" is proposed for the northwestern unit.

The Interior Low Plateau physiographic province as defined by Fenneman[2] consists of a plateau area bounded on the east by the loftier Appalachian plateaus, on the south and west by the overlapping edge of the Cretaceous coastal plain sediments, and on the north by the overlapping southern edge of the glacial drift. Into the low plateau are countersunk two basins, the Nashville Basin in central Tennessee and the Lexington basin in north-central Kentucky. The tilted and beveled Carboniferous rocks of the surrounding plateau stand out in sharp relief above these basins, rimming them in with ragged, dissected escarpments. This plateau area, surrounding the basins, has been called by Fenneman the Highland Rim section. For some time it has been recognized that the characteristics of this section are not uniform, and that further investigation might be expected to lead to further subdivision. The object of this paper is to propose a logical basis for such subdivision, as a result of reconnaissance work in Kentucky and Tennessee and of notes made on a later trip through southern Indiana during the summer of 1925.[3]

That part of the plateau area which immediately rims the two basins, including the whole of the area in south-central Kentucky which lies between the basins, is essentially a physiographic unit.

[1] Published with the consent of the Director of the Kentucky Geological Survey.

[2] N. M. Fenneman, "Physiographic Divisions of the United States," *Annals of the Association of American Geographers*, Vol. VI (1917), p. 59.

[3] Information as to the position of the Dripping Springs escarpment between Munfordville and the Ohio River has been kindly supplied by Dr. J. M. Weller, of the Kentucky Geological Survey.

It consists of a fairly flat-topped, deeply dissected bench or plateau developed predominantly upon resistant Mississippian strata, in which the uniform character of the component hard limestones and sandy shales results in broad uniformity of topographic expression. The strata have been beveled, but the beveling has been diversified,

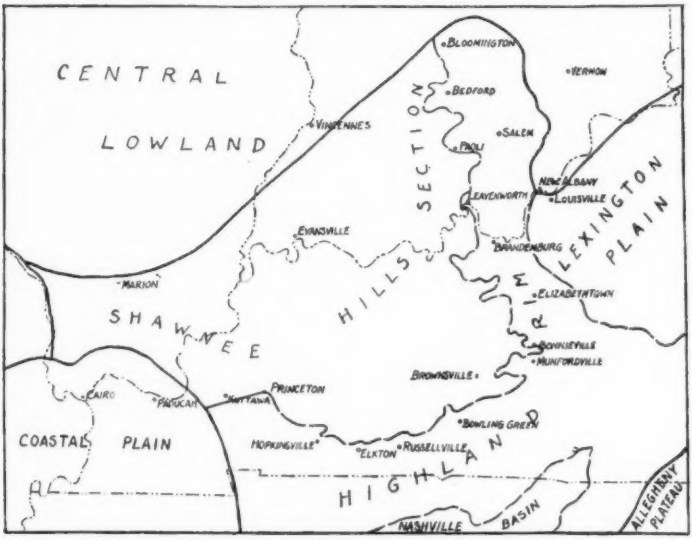

FIG. 1.—Sketch map showing the broad relations of the northwestern portion of the Interior Low Plateau province. The area designated as "Highland Rim" has been referred to as the "Mississippian Plateau" and also as the "Pennyroyal Plateau" (C. O. Sauer, "Geography of the Mississippi Plateau" (*Kentucky Geol. Surv.*, Series VI, Vol. 25 [1925]). Although these terms thus have priority in Kentucky literature, the term "Highland Rim" is used here since it follows the standard usage adopted in the treatment of the Interior Low Plateau province as a unit.

notably in southern Kentucky, by later vigorous differential etching in the softer strata, which has resulted in the development of broad parallel corrugations in the present plateau surface. The inner edges of the plateau are held by massive Lower Mississippian limestones which have probably checked the dissection of the Highland Rim since Tertiary times and has thus preserved the upland levels. Summit elevations range from 500 feet to 1,200 feet, averaging nearly 1,000 feet east of the Nashville basin and less than 800 feet west of

it. Certain interfluves in the western portion, however, reach an elevation of 1,000 feet. The present drainage antedates the present basin-and-plateau topography; hence the streams flow generally westward in intrenched channels and with dendritic pattern. The rock structure is too nearly horizontal to exercise extensive drainage control. The individual valleys are deep with moderate side slopes, and the interfluves are relatively broad. Because of these characteristics it is evident that one might travel completely around the plateau rim of the Nashville basin without discovering variable topographic factors other than local degree of dissection. This region is hereafter referred to as the Highland Rim.

The remaining part of the plateau area, namely, the portion which lies in northwestern Kentucky, Illinois, and adjacent Indiana, has peculiar topographic characteristics which differ from those of the Highland Rim. They are as follows:

1. Strong dissection, with much smaller interstream areas than in the Highland Rim, and with notably steep slopes held up universally by the cliffy sandstones and conglomerates of Pennsylvanian and Chester age. The result is a much more sharply rugged surface than that which characterizes the Highland Rim, where even in the deeper valleys the side slopes are gentler; and this ruggedness is typical of the northwestern region.

2. Greater local relief, averaging 200–300 feet as compared with an average of 100–200 feet in the Kentucky portion of the Highland Rim.

3. Low summit elevations, for the most part lower than the lowest such elevations in the Highland Rim, and nowhere exceeding 700 feet except in isolated residuals.

4. Extensive alluvial filling in the downstream portions of the larger streams tributary to the Ohio. It is likely that this filling is the result of Pleistocene ponding and alluviation aided by decided differential downwarping to the northwest in late Tertiary or Quaternary time.[1]

5. Strong and complex faulting in a belt trending nearly east-west, bringing up the Chester and Pennsylvanian sandstones in such

[1] W. R. Jillson, "Valley-Filled Area of the Western Kentucky Coal Field," *Pan American Geologist* (May, 1927).

a way as to maintain the characteristic of steep slopes and sharp relief over an area in Livingston, Lyon, Crittenden, Caldwell, and Trigg counties in western Kentucky and adjacent counties in Illinois, which, if not faulted, would possess today the characteristics of the Highland Rim.

There are then two distinct natural regions, each with special characteristics, composing the Interior Low Plateau exclusive of the two contained basins. The question of a dividing boundary between them next arises. Such a boundary is present, and is easily traceable both topographically and geologically if certain local compromises

FIG. 2.—The Dripping Springs escarpment. Looking north from the low sink-pitted limestone area near Bowling Green, Kentucky. (Photograph by W. R. Jillson.)

be allowed. It consists of the strong, dissected but wall-like escarpment (Fig. 2) known in the Mammoth Cave region as the Dripping Springs escarpment. It is developed on the outcropping edge of the hard Cypress (Chester) sandstone, which dips northward and westward. The escarpment faces south in southwestern Kentucky and east in central-western Kentucky, and overlooks the corrugated Highland Rim plateau from a height of 160 feet throughout the region north and west of the escarpment. The characteristics before enumerated are universally displayed, because of dominant control of topography by cliffy sandstones: principally the massive Pennsylvanian beds, but notably also the fringing Chester sands (Bethel, Cypress, Hardinsburg, and Tar Springs formations, and their correlatives). Limestones and shales are markedly subordinate.

This escarpment with persistent characteristics extends east and

north from the vicinity of Princeton, Caldwell County, Kentucky, where its continuity to the west is broken by the fault zone already indicated, to and beyond the Ohio River. It has many small butte-like outliers which, because of their subordinate position, must be assigned to the Highland Rim near whose outer edge they stand. Plateau inliers within the rampart of the Dripping Springs escarpment are very rare.

The stratigraphic contact which is coincident with the boundary in question may be readily interpolated on the Geologic Map of Kentucky[1] although it does not show as the map is drawn. From the vicinity of Princeton the line trends southeast, passing close to, but north of, Hopkinsville. North of Elkton it swings northeast, passing north of Russellville and Bowling Green at close distances. Near Munfordville, Green River has cut a pronounced re-entrant into the escarpment, which at Bonnieville, a few miles north of the River, reaches its easternmost extent.

North of Green River the trend is northeast through Hart, Grayson, Hardin, Breckinridge, and Meade counties with minor salients and re-entrants which are responses to local interfluves and drainage lines. Throughout this region the escarpment is continuous, but not quite so high nor so abrupt as it is to the southwest. The boundary reaches the Ohio River between Brandenburg, Kentucky, and Leavenworth, Indiana, where it loses its identity for a short distance in the high river bluffs. A westward dip carries the escarpment-forming Cypress horizon down to water level within a short distance, in consequence of which there is no long westward re-entrant to complicate the boundary. Northward in Indiana this boundary finds its logical continuation in the outcrop of the base of the Huron group of Indiana geologists. This group correlates with the Chester series and exhibits in general the same lithology as the Chester in Kentucky. A comparison of the Indiana (1903) and Kentucky (1923) geologic maps with the addition of the line of outcrop of the Cypress sandstone in Kentucky shows at once the continuity of the Cypress-basal Huron horizon. The line trends north through Crawford County, touches the southwest corner of Washington County, runs close to the town of Paoli, and continues north through Orange and Lawrence counties (west of Bedford) to a point west of Bloomington in

[1] *Kentucky Geol. Survey*, Series VI, 1923.

Monroe County, where it is intersected by the border of the glacial drift, the northern boundary of the Interior Low Plateau province.

Although it forms a distinct escarpment west of the Blue River in Indiana, the Huron outcrop loses this characteristic to the north, and is most notable as a line separating, on the east, gently rolling topography developed in limestones from rough and broken country to the west, in which relief (about 400 feet) is sharply controlled by sandstones of the Upper Mississippian and Pennsylvanian. There is no essential difference between the elevations of the sandstone-capped interfluves west of this line and those of the limestone belt on the east; it is rather in the steeper individual slopes and more rugged hills that the striking difference is found. The reason for the sharp relief in the sandstone-capped areas is obvious. The contrasting gentler character of the limestone belt is to be attributed probably to (1) extensive development of sinkholes, which greatly interfere with surface run-off and permit weathering to become a relatively more effective factor in producing gentle slopes; and (2) the presence of pure limestones, which tend to break down into gentle slopes even where surface run-off is effective.

It is true that farther east, in the zone where the Knobstone horizon is at the surface, producing a pronounced escarpment, the sharpness and depth of dissection are locally as great as in the sandstone area west of the boundary under discussion. This situation is analogous to the deep dissection found in other parts of the Highland Rim plateau in Kentucky and Tennessee, as for example along the Cumberland River in the region about Celina, Tennessee, and along Barren River above Bowling Green, Kentucky.

Since the topographic expressions of the areas on both sides of the boundary just drawn continue in all their essentials from western Kentucky into Indiana to the northern boundary of the province, the Highland Rim section may logically be continued northward to the drift border, between the Knobstone escarpment on the east and the Huron outcrop on the west. To this arrangement a study of the map reveals a possible alternative, namely, the limiting of the Highland Rim section in the area north of the Ohio River to the narrow strips lying east of the Knobstone escarpment, and thus including the area west of the latter with the rugged northwestern Kentucky-

Illinois section. The only argument in favor of such a division is that the Knobstone escarpment separates topography typical of the Lexington plain from deeply dissected topography on the west. Counter considerations, however, are three in number: (1) the deep dissection west of the Knobstone escarpment is largely caused by proximity to the Ohio River and its immediate tributaries and becomes steadily less pronounced to the north. (2) The Knobstone escarpment is the true topographic and geologic continuation[1] of the crest of the Highland Rim around the Nashville and Lexington basins. (3) The outcrop of the base of the Huron group, west of the Knobstone escarpment, has been shown to be a line separating physiographically contrasting areas.

It has been stated that the vicinity of Princeton, Kentucky, marks the western limit of the continuously traceable Dripping Springs escarpment. Through the remaining distance of less than thirty miles between Princeton and the province boundary near the Tennessee River the line must be somewhat generalized. If, however, a straight line be drawn southeast from Princeton through Kuttawa and thence on to the province boundary, the faulted area on the northwest in which Chester and Pennsylvanian sandstones are brought into dominant topographic significance will be separated with a very small degree of error from an area of low relief on the southeast underlain principally by limestones.

Neither the arbitrary character of this dividing line through the western fault zone nor the gradual change in its aspect north of the Ohio River lessens its value as a natural boundary. At no point is the change in character of the two physiographic units separated by this line gradual or transitional. It is suggested that the term "Highland Rim Section" be restricted to that area within the Interior Low Plateau Province which, exclusive of the Nashville and Lexington basins, lies east and south of the boundary drawn; and that the term "Shawnee Hills Section" be applied to the area north and west of it. The latter term, commonly applied to the rugged hills in southern Illinois, is suggested because it is the only adequately descriptive term given to any considerable area within the proposed new section.

[1] I.e., The lithologically persistent outcrop of the massive Lower Mississippian beds.

A RESTORATION OF THE ANASPID *BIRKENIA ELEGANS* TRAQUAIR

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ABSTRACT

This paper is a detailed anatomical study of the Scottish anaspid Birkenia from new material, together with a discussion of the relationships of the families in this class.

INTRODUCTION

The specimens for this study were obtained for the Museum of Comparative Zoölogy by Messrs. Tait and Strachan of the Scottish Branch of H.M. Geological Survey during the spring of 1927, from the Downtonian of Lanarkshire and Ayrshire. My thanks are also due to Dr. P. E. Raymond for much helpful advice in the laboratory, and to Miss E. L. Stetson for making the drawings.

Since the publication by Kiaer[1] of his monograph on the Norwegian anaspids describing his wonderfully preserved material, it is possible to work out with greater certainty many of the anatomical details of the more poorly preserved Scottish forms. Kiaer's discovery of the pineal opening, and of the unpaired nasal opening, proved that Traquair, orienting the animals on the basis of a supposedly heterocercal tail, had confused the dorsal and ventral sides. Traquair's material evidently yielded very little structural detail, as the cranial roof, the pectoral spine apparatus and branchial openings, the anal fin structure, and the caudal fin are either incorrectly figured, or else omitted. Lack of a binocular microscope was doubtless a great handicap. The scale system of the body is correctly interpreted.

I have failed to find any new species or genera in my material. In the anaspids Traquair[2] erected one family, Birkeniidae, with two

[1] J. Kiaer, "The Downtonian Fauna of Norway," *Videnskapsselskapets Skrifter*, I. Mat.-naturv. Klasse, 1924, No. 6.

[2] R. H. Traquair, "Report on Fossil Fishes . . . . in the Silurian Rocks of the South of Scotland," *Trans. Roy. Soc. Edinburgh*, Vol. XXXIX (1898).

distantly related genera, Birkenia and Lasanius. Abel[1] made these two genera into families, each with a single genus. Kiaer adopted his view, and in addition made three families to receive his Norwegian forms, each containing but a single genus and species.

THE SCALES

In thin-section the scales of Birkenia show absolutely no trace of structure, appearing as an opaque carbonaceous mass. Both Traquair and Kiaer failed to find any structure in their material. The original substance has been so altered that there is little hope of ever finding a clue to this important point from material now available. The scales exhibit in cross-section the same interlocking device figured by Kiaer[2] for the Norwegian forms. In specimens preserving the original scale substance in this altered form, no trace of surface ornamentation is visible. The scale is smooth and of a graphite-like consistency. Occasionally, however, very delicate casts of the exterior are found, and the scales from all parts of the body, including the head and the dorsal scutes, are seen to be closely set with small pustules. This shows out particularly well in Figure 5.

PECTORAL FIN SPINES

The pectoral spines and post-branchial plate, as Kiaer calls them, occur in Birkenia, as well as in the Norwegian forms, although they are not mentioned by Traquair. The post-branchial plate, which lies behind the line of the branchial openings, corresponds more closely in shape to the post-cephalic rods of Lasanius than does the same structure in the Norwegian forms. The lateral portion is 9–10 mm. long, thickening toward the base. The basal portion, about 3 mm. long, makes an abrupt angle with the lateral member, as do the rods in Lasanius, and projects downward and inward toward its fellow from the opposite side. The triangular pectoral plate is situated at the angle of the ventral and the lateral scale systems, just behind the post-branchial plate. The dorsal member of this triangular plate is intercalated with the lateral scales; the ventral member, with the ventral scales. The third angle bears a short spine,

[1] O. Abel, *Stämme d. Wirbeltiere* (1919).

[2] J. Kiaer, *op. cit.*, Figs. 28 f., p. 63.

and projects along the line of junction of the two scale systems. In large specimens the dorsally projected member is about 5 mm. long; the ventral, about 4 mm.; and the third projection, exclusive of the spine, is about 3 mm. I have only one fragment of the spine, 3 mm. long, which probably does not represent its total length. The branchial openings are eight in number, and each is bounded on the bottom by a horseshoe-shaped rib, the ends of which are inserted

FIG. 1.—Post-branchial plate (left) and pectorial plate (right) of *Birkenia elegans*. Note the length of the former. The latter bore a spine at the posterior angle. The branchial openings cannot be distinguished. Anterior left, posterior right. About 6×. M.C.Z. No. 2006.

between the scales bordering the branchial band. The state of preservation makes it impossible to make out further details of this region.

Kiaer homologizes the post-branchial and the pectoral plate of the Norwegian forms with the post-cephalic rods of Lasanius, and such an homology is entirely justified. There is this important difference which must be noted, however. The rod structure in Lasanius is subdermal, while the plates in all the other anaspids are dermal. In the former the most perfectly preserved rods and casts of

rods show absolutely no trace of surface ornamentation, even though the very thin, delicate scales of the anterior part of the body, and the six branchial ossicles, do carry such ornamentation.[1] This points to a subdermal position. On the other hand, in Birkenia and in the Norwegian forms, the post-branchial and pectoral plates are ornamented with the fine granulation; therefore their position must have been dermal. I shall return to this significant point later.

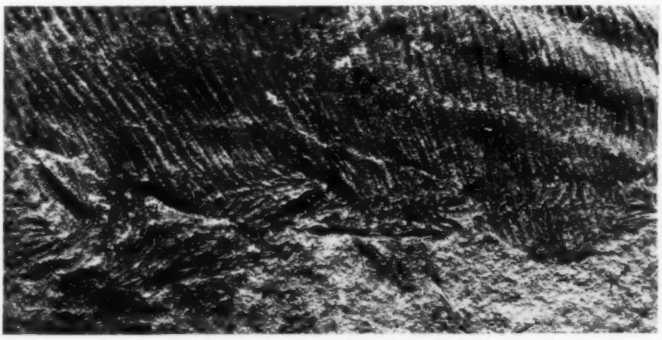

FIG. 2.—Anal fin and pre-anal spine of *Birkenia elegans*. The anal fin is at the right. The semicircular saddle plate and the small spine may be seen between the two. The post-branchial and pectorial plates, imperfectly preserved, are visible to the left, together with some crushed plates from the lower part of the body. Anterior left, posterior right. (See Fig. 7.) About 4½×. No. 1573.

THE ANAL FIN

The anal fin is not the simple, rounded structure that Traquair supposed. It is made up of two ranks of scales. The heavier basal ones are but the continuation of the body scales. At a line approximately half the width of the fin, they give place to a finer rank which continues back as a fringe toward the posterior end. There is no spine bounding the anterior edge of the fin, as in the Norwegian forms; but there is a semicircular saddle plate situated at the angle of the fin and the body. Anterior to this saddle plate is a small spine; and anterior to this is the large, free-standing, pre-anal spine, triangular in cross-section. The anal opening, as Kiaer has shown,

[1] H. C. Stetson, "Lasanius and the Problem of Vertebrate Origin," *Journal of Geology*, Vol. XXXV, No. 3, pp. 247–63.

lies just behind the pre-anal spine at the termination of the ventral scale system.

THE STRUCTURE OF THE HEAD REGION

The scale arrangement of the throat and side of the head are correctly drawn in Traquair's restoration.[1] There seem to be no median gular plates such as Kiaer finds in Rhyncholepis. The two patches of small lancet-shaped scales seem merely to divide at the median line. The curious patch on the forepart of the head that Traquair figures, exists on all specimens that I have examined. It is, of course, paired and is made up of fine lancet scales perpendicular to the larger ones of the head. This patch is found to lie just below the oral opening and may represent the delicate, more flexible covering of the "cheeks" (Fig. 5).

The floor of the mouth consists of three or four rows of heavy lancet scales, lying just above, and anterior to, the "cheek patch." The roof of the mouth is made up of three or four heavy plates, extending over the floor in a beak-like projection (Fig. 3). As the former are part of what Kiaer calls the "lateral rostral plate area," forming part of the cranial roof, they will be taken up in that connection.

The "rounded marking" that lies "on the wrong aspect of the head for an orbit,"[2] nevertheless turns out to be that organ when the animal is reversed. In one specimen two plates of the orbital ring are well preserved. Judging by the size of these two, it would take four to complete the circumference of the orbit, although in Pterolepis they are unequal in size.

THE STRUCTURE OF THE CRANIAL ROOF

This has proved the most difficult feature to determine, as the plates are small and fragile and easily crushed. In fact, so distorted are most specimens that it would have been practically impossible to restore the cranial roof if it were not for Kiaer's schematic drawings of the Norwegian forms. In Pterolepis the structure of different parts of the cranial roof varies somewhat in different individuals. This is also the case with Birkenia, and therefore, as with

[1] R. H. Traquair, *op. cit.*, Fig. 3, p. 838. [2] R. H. Traquair, *op. cit.*, p. 838.

Kiaer's reconstructions, Figure 4 is necessarily diagrammatic. Furthermore, no one specimen shows all parts of the cranial roof complete. It bears closer resemblance to Pterolepis than to either Pharyngolepis or Rhyncholepis, in that there are numerous small plates instead of relatively few large ones. Their arrangement is likewise very similar.

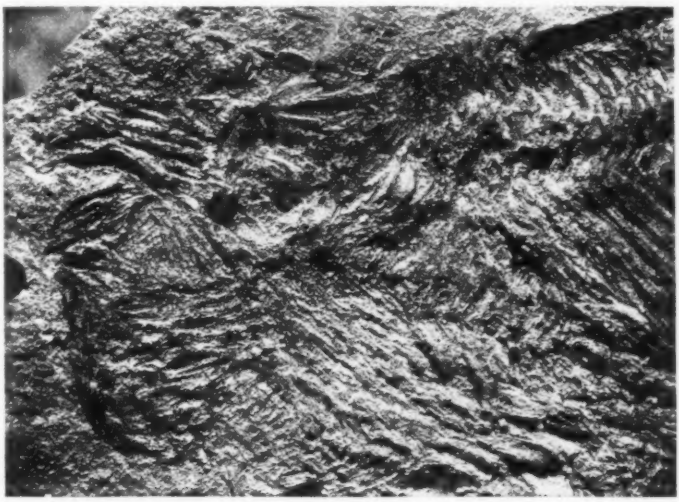

FIG. 3.—The anterior part of the body of *Birkenia elegans* crushed obliquely from the top and from the side. The mouth is open. Note the series of plates forming the floor of the mouth, and the plates of the rostral area which form the curving roof. The distortion of the head gives it a blunted appearance, and the mouth has been displaced dorsally. The pineal plate is visible dorsally, broken free from the head. (See Fig. 4.) Anterior left, posterior right. About 4×. M.C.Z. No. 2006.

In describing the plates of the cranial roof, I am adopting the terms used by Kiaer; and I am also considering it to be limited by the same plates.

The pineal plate, which is the median plate of the whole system, is very markedly Y-shaped. The fork of the Y is bounded by a strong rib, and its arms inclose the narial opening. Ahead of this lies a broad, triangular, median rostral plate, excavated posteriorly to form the anterior border of the nostril. This is evidently a modi-

fication of the small median rostral plate occasionally found in Pterolepis[1] and the larger one found in Pharyngolepis.[2] The apex of this triangular plate is bounded by two heavy, curving plates, meeting anteriorly and springing from the arms of the pineal plate. The lateral rostral plates are four to five in number. The outside pair are

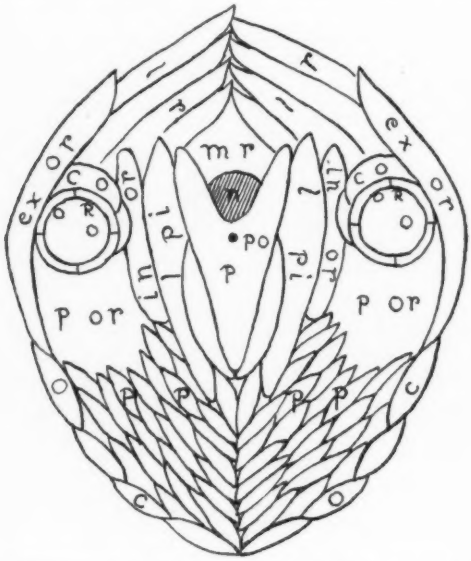

FIG. 4.—Diagrammatic sketch of the cranial roof of *Birkenia elegans*. *c. o.*, circumorbital; *ex. or.*, external orbital; *in. or.*, internal orbital; *l. pi.*, lateral pineal; *l. r.*, lateral rostral; *m. r.*, median rostral; *n.*, nostril; *o.*, orbit; *oc.*, occipital; *o. r.*, orbital ring; *p.*, pineal plate; *p. o.*, pineal opening; *p. p.*, post pineal area; *p. or.*, post-orbital. Anterior top, posterior bottom.

the heaviest and form the anterior edge of the upper half of the mouth. On either side of the pineal plate lie the two heavy lateral pineal plates, and outside of these are the internal orbital plates. The eyes are bounded anteriorly by two circumorbital plates and posteriorly by the large posterior orbital plate. This latter plate varies considerably as to size and shape in different individuals. The external orbital plates lie ventrally to the eye. They are very heavy

[1] J. Kiaer, *op. cit.*, Fig. 16*a*, p. 38. [2] *Ibid.*, Fig. 20, p. 44.

and join anteriorly the outermost lateral rostral plates. The post-pineal area is made up of small lancet scales, dividing on either side of the median line. Outside of these, and marking the posterior limits of the head, lie the occipital scales, which are but slightly larger than those of the post-pineal area.

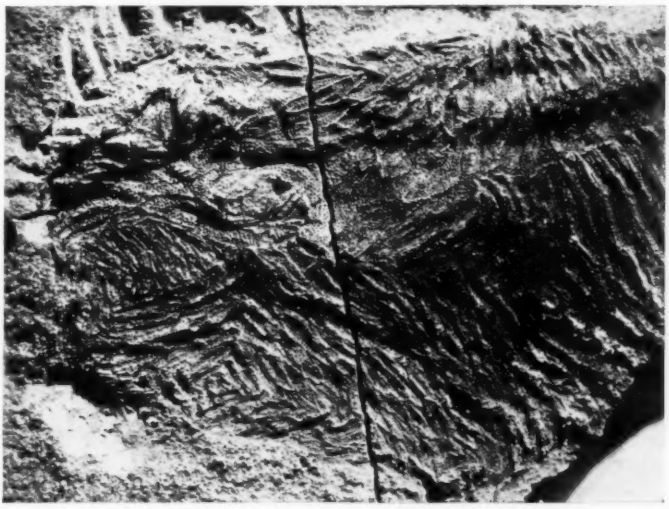

FIG. 5.—The head of *Birkenia elegans* crushed obliquely from above and from the side. Note the scales of the post-pineal area meeting at the mid-line near the top of the figure. All the plates from the left side of the cranial roof are distinct, with the exception of the median rostral plate and the lateral rostral plates. (See Fig. 4.) Note also the lozenge-shaped patch of very narrow scales on the "cheek," and the position of the orbit, lying just above and behind this patch. The granular ornamentation of the scales is clearly shown. About $5\frac{3}{4}\times$. M.C.Z. No. 1569.

THE CAUDAL FIN

The caudal fin is, of course, reverse heterocercal, or hypocercal as Kiaer has called it. The general contour is as Traquair shows it, but the fin membrane is continuous and not restricted to the ventral side of the lower lobe. The main body axis continues to the end of the lower lobe, and the long scales of the trunk become finer and finer as they approach the tip. The two sets meet at an angle at

the mid-line, and do not run diagonally across, as in Traquair's figure. Contrary to what Kiaer finds in Pterolepis, the fin membrane is covered by a double row of "fulcral" scales on the lower side, and therefore Traquair was not mistaken in what he saw. The scales of the outer row are narrower and longer than the inner, but their long axes point in the same direction. The inner row of stouter "fulcral" scales continues around to the dorsal side, as does the outer row, which become longer and thinner as they progress. This outer row finally merges with the epichordal lobe of the tail. The epichordal lobe is completely covered with very small, narrow scales running at right angles to those of the body, and when well preserved shows no trace of fin rays. In specimens that are somewhat disintegrated, however, these inner radial elements show plainly in the epichordal lobe and in the upper side of the caudal fin membrane.

No trace of a notochord has ever been found in any anaspid. If it were present at all, no chondrification can have surrounded the sheath. If there were no vertebral stiffening rod, there could be no place of attachment for the caudal muscles such as are found in modern heterocercal and homocercal tails. Hence the caudal fin necessarily drooped. It should be noted that in the Acanthodidae a vertebral column is found with well-developed neural and haemal arches.

THE DORSAL SCUTES

The dorsal scutes exhibit great diversity of form. In the other anaspids the variations are mainly those of size. The anomalous, double-hooked scute exists in all specimens that I have examined (so preserved as to show the scutes at all); and it is not, as has been supposed, a mistake of Traquair's (Fig. 6). It is divided by a vertical suture, and appears to be formed by two of the thorn-shaped scutes growing close together, so that the point of one is reversed. Anterior to this peculiar scute are five others, four of which are flat-lying ridge scales. Posteriorly are four thorn-shaped scutes, growing progressively smaller (Fig. 7).

RELATIONSHIPS

Kiaer takes six important anatomical features and, by comparing them in each of the genera, arrives at certain conclusions as to their

interrelationships and the extent to which specialization has been carried.[1] These features are: the anal fin, the lateral scale system, the paired pectoral spines, the branchial openings, the structure of the mouth, and the cranial roof. I shall add one more, the dorsal scutes.

The anal fin of Birkenia comes nearest to that of Pharyngolepis, which Kiaer considers the most primitive, in this respect, of the Norwegian forms. It is even simpler in structure than the latter, as the fin itself bears no bordering spine.

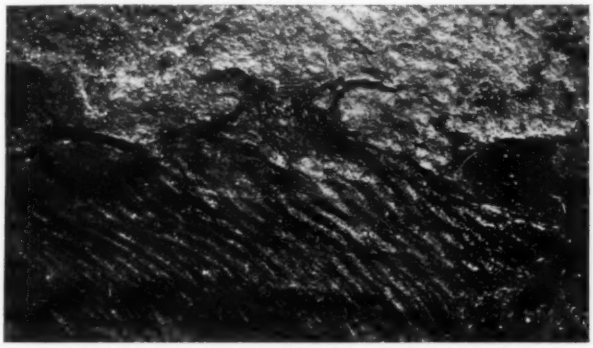

FIG. 6.—The mid-dorsal scute of *Birkenia elegans*. About 7½×. M.C.Z. No. 2007

The lateral scale system of Birkenia is considered by Kiaer to be the most specialized of all, as it most closely approaches the type found in the Palaeoniscidae (Fig. 7). The upper rank of scales from the posterior half of the body follows the course of the other body scales and does not slant forward as does the anterior half of this same row. The palaeoniscid plan is completed in *Euphanerops longaevus* Woodward. The Norwegian forms have the whole of the dorsal rank slanting forward.

The pectoral spine apparatus is larger; and the post-branchial plate is as large as that of Rhyncolepis, which Kiaer considers on the whole to be the most specialized. The latter plate resembles Lasanius, in that the dorsally projected member is unusually long. It is by no means certain just what here constitutes specialization. If

[1] *Ibid.*, p. 126.

mere size is the criterion, then Lasanius is the least primitive. In fact, it is extremely doubtful if Lasanius can be compared in this respect with the other anaspids. Both types of structure probably represent end-products along their own lines.

The branchial openings are eight in number; and as Kiaer points out, if we assume that large numbers are primitive, then Birkenia, and Lasanius with seven, are the most specialized in this respect.

The structure of the mouth seems to indicate a position between the primitive Pterolepis and Pharyngolepis, which is next in line. In Birkenia the plates are somewhat larger, and fewer in number than in Pterolepis.

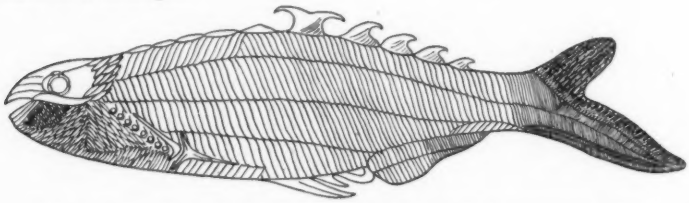

FIG. 7.—Restoration of *Birkenia elegans* Traquair. This restoration differs from Traquair's in the structure of the head region, the cranial roof, the anal fin, and the caudal fin, and by the addition of the pectoral and post-branchial plates. About ½×.

The cranial roof indicates a somewhat similar position although it approaches closer to Pterolepis. There is a median rostral plate; this and the large plates at the anterior part of the mouth are the main points of resemblance to Pharyngolepis. On the other hand the rostral area is made up of many smaller plates, as in Pterolepis. Excavating the marial opening a little deeper into the pineal plate would give the Y-shape of this plate in Birkenia. The lateral pineal plates, the circumorbital plates, the occipital scales, and the post-pineal area correspond closely to Pterolepis.

In regard to the dorsal scutes, Birkenia shows the highest degree of specialization. Nothing comparable to the variety here displayed is found in the other anaspids.

CONCLUSION

It is obvious from the foregoing synopsis that no progressive development is indicated. Birkenia is primitive in some respects, spe-

cialized in others; and the Norwegian forms are similarly intermingled. Kiaer admits that as yet no natural groups can be set up among the anaspids. He therefore regards them as the scattered remnants of a large group and makes for each a separate family. I entirely agree with Kiaer in this interpretation. The group represents a good example of radial evolution. But I cannot accept Lasanius as the genus which is nearest the ancestral form. Birkenia, the three Norwegian forms, Euphanerops, and *Ctenopleuron nerepisense* Matthew represent end-products of small branches from the same main line. Standing over against all of this group, is Lasanius on another main line, itself as far advanced on its particular course of development as any of the others. The pectoral spine apparatus is *internal*, except the fin spines, and from its structure and position serves as a visceral skeleton.[1] The pectoral and post-branchial plate of the other anaspids can be homologized with this more complicated structure, but they are *external*. Therefore, it is difficult to see how such an endoskeletal structure, that must have acquired great functional importance,[2] can be considered to have given rise to the reduced external elements that Birkenia and the Norwegian forms possess. If the anatomy of the other anaspids indicates radial evolution, Lasanius makes the argument even more sound.

Kiaer points out that the body scales of the anaspids undoubtedly follow the course of the myotomes. If we postulate an ancestral form as naked, or, at most, covered with thin scales and having pectoral fin folds, those scales developing above the fin would naturally be used as an anchorage for the fin rays, and this would accentuate their development. Along one line these heavy scales become part of the endoskeleton and acquire the stiffening function of a visceral skeleton, while still serving as supports for eight fin rays. In addition, Lasanius has kept a very light scale covering and was therefore the most active of all the anaspids. Along another line, that of Birkenia and the Norwegian forms, the body supports of the primitive fin rays become reduced in number, leaving only the curiously shaped post-branchial and pectoral plates, the latter with only a single spine. These plates remain part of the exoskeleton.

[1] H. C. Stetson, *op. cit.*, pp. 255–57.

[2] *Ibid.*, Fig. 1, p. 250; Fig. 2, p. 251; Fig. 3, p. 258.

This has most certainly been the history of the latter division, for, as Kiaer points out, in Pterolepis are found several very small spines behind the large pectoral spine. This form, therefore, has not progressed quite as far as the others in the modification of the primitive fin-fold condition.

I wish to reiterate once more a point which does not seeem to be very widely appreciated. The anaspids are the oldest animals known that have a normal, fusiform fish-shape. The notochord either had not yet developed or was in a very rudimentary condition. The mouth structure indicates a condition that antedates the formation of true jaws. One of them, Lasanius, has a type of endoskeleton that is unique, which from its position alone could not help acquiring functional importance. Is it not some such group as this that must be relied upon, in some measure, to bridge the gap that lies between the true fishes and their invertebrate ancestor?

ON THE ORIGIN OF THE ALKALINE ROCKS

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ABSTRACT

The writer believes that the process of albitization, now known to be a common accompanying feature of granitic intrusion, furnishes a key to the genesis of alkaline rocks. The passage of emanations rich in soda and alumina, which albitization phenomena show have occurred, may in favorable instances have desilicated a granitic magma and so enriched it in soda and alumina that nephelite would crystallize, and after consolidation, soda-rich deuteric minerals form.

Professor Tyrrell,[1] in his recent excellent short treatise on the *Principles of Petrology*, gives a concise summary of present ideas on the problem of the genesis of the alkaline rocks. Some petrographers hold that the desilication of the magma has been caused by assimilation of limestone; while others believe that the unique character of alkaline magma has been reached by more ordinary differentiation processes, and that the association of some alkaline rocks with bodies of limestone is fortuitous.

The possibility of considering that some other processes of differentiation may have formed the alkaline rocks has occurred to the writer. No claim is made that all alkaline rocks have come into being in the manner herewith proposed. Simply another method is suggested of desilication of magma and of its enrichment in soda and alumina.

A number of facts concerning alkaline rocks have been established beyond doubt. Briefly stated, these facts are: (1) Alkaline rocks are subordinate in volume in comparison with other rocks, and probably constitute less than 1 per cent of the whole. (2) Alkaline rocks are generally associated with a plutonic sequence of subalkaline rocks, and represent the last of the series to be intruded or to crystallize. (3) Alkaline rocks at the time of their crystallization were exceptionally rich in volatile constituents; and the mineral-

[1] G. W. Tyrrell, *The Principles of Petrology* (1926), pp. 167–70.

izers have been in some way responsible for, or have aided in, producing their peculiar character.

Examples of rock masses and plutonic provinces illustrating these points have been given by Shand.[1]

It seems to the writer that two authors have come remarkably near to an explanation of the genesis of these interesting rocks, but one has omitted some of the other's reasoning to give to his own the essential points for completing the story. C. H. Smythe,[2] to show that volatile constituents were abundantly present during the crystallization of alkaline rocks, directed attention not to the dominant constituents, but to those which, though small in amount in the solid rock, prove that volatile constituents were present in quantity in the magma. Because of these volatile emanations the magma was enriched in lithium, beryllium, the rare earths, and halogens. Smythe does not consider that they may also have enriched the magma in the alkalies themselves, although the reader is possibly allowed to infer that such may have taken place.

The second writer, Bowen,[3] has shown that during the crystallization of granitic rocks the magma was enriched in the $NaAlSiO_4$ molecule, as well as in the volatile constituents. Bowen, however, has proceeded to derive the residual magma from which nephelite was to crystallize, by a sinking of quartz, biotite, potash feldspar, etc., out of a granitic magma during its crystallization.

Fenner[4] has given us cause for doubting the universal application of crystal sinking in magmatic differentiation and the genesis of all alkaline magmas by sinking of crystals of moderate specific gravity as quartz, alkali feldspar, and biotite seems too delicate a process. Bowen has established, however, the important fact that the residual magma is enriched in soda. Thus the first step in

[1] S. J. Shand, "The Problem of the Alkaline Rocks," *Proc. Geol. Soc., South Africa* (1922), pp. 19–32.

[2] C. H. Smythe, Jr., "Composition of the Alkaline Rocks, and Its Significance as to Their Origin," *Amer. Jour. Sci.* (4), Vol. XXXVI (1913), pp. 1–36.

[3] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, Vol. XXIII (1915), Suppl., p. 56.

[4] C. H. Fenner, "The Katmai Magmatic Province," *ibid.*, Vol. XXXIV (1926), pp. 700–703.

the genesis of alkaline rocks as demanded by Shand,[1] the concentration of alkali molecules, has been accomplished.

In corroboration of Bowen's idea that the residual magma would be enriched in soda and alumina is the evidence stressed in recent years that a post-magmatic process of albitization has closely followed the crystallization of a great many granitic rocks and pegmatites. In a previous paper the author[2] has described a locality where such a process had operated, and he has listed the names of other authors who have contributed to this same study.

The proof that albitization is one of the normal accompanying features of large-scale igneous intrusion may form a link in our knowledge of the genesis of the alkaline rocks. The writer's study of examples of many alkaline rocks in the collection of the Massachusetts Institute of Technology has shown him that nephelite, when present, was usually one of the late pyrogenetic minerals, and that the rock had begun to crystallize as a subalkaline one, but during the progress of crystallization the magma became much richer in soda. After consolidation the rock was invaded by soda-rich emanations so that the feldspars have been intensely albitized and soda-bearing deuteric minerals such as sodalite, cancrinite, riebeckite, and aegirite have formed in many instances.

The passing of soda- and alumina-bearing emanations through a subalkaline magma, thus enriching it in these elements, may thus have been one process by which alkaline magmas have come into being. This process of differentiation by the passage of volatile material through a still liquid or partially liquid magma has been suggested by Fenner.

Fenner says:

> We may favorably entertain the tentative view of most volcanologists that there is probably a streaming of gases through the magma reservoir from lower levels toward the surface, some of it escaping through volcanic conduits and some penetrating the rock walls, and we may inquire into the consequences of this conception.
>
> The equilbrium in a mixture of gases is dependent upon the temperature

[1] S. J. Shand, *op. cit.*, p. 28.

[2] J. L. Gillson, "The Granite of Conway, New Hampshire, and Its Druse Minerals," *Amer. Mineral.*, Vol. XII (1927), pp. 307–19.

and pressure. The differences of pressure between the lower and higher levels of a large magma body must be very great. In the ascent of a gas bubble reactions among its constituents will ensue, of such sort as to increase the molecular numbers. Reactions with the surrounding magma will likewise take place. Some substances will be given up to the magma and others taken into gaseous solution.[1]

It seems to the writer that the process of differentiation suggested by Fenner is a very important one, and that many examples will soon be described,[2] now that the attention of petrographers has been directed toward it. The application of such a process of differentiation to the genesis of the alkaline rocks would lead, possibly, to the following reasoning:

A cupola of granitic magma, in process of crystallization following the usual and normal order, was situated above a large body of which it was simply an upper part, and the whole mass was originally of uniform composition. Were the roof of proper shape, the volatile materials given off during crystallization of the larger body and containing the $NaAlSiO_4$ molecule must pass, in great part, through the upper cupola, there to react with liquid and solid phases. Shand has noted that many richly alkaline rocks occur in cupolas, volcanic pipes, or in fissures, through which magmatic gases might have streamed for long periods.

In the cupola, therefore, soda-rich biotite, amphiboles, pyroxenes, and feldspars crystallized during the later stages of the consolidation of the originally granitic magma, because of the introduction into it of such a large amount of soda from below. With the progress of this late crystallization, the silica content of the residual magma in the cupola was reduced to so great an extent that nephelite began to crystallize. Continued passage of the soda-rich solutions after solidification of the mass in the cupola carried on albitization of the feldspars, and formed the deuteric minerals, sodalite, cancrinite, aegirite, etc., found in so many alkaline rocks.

[1] C. N. Fenner, *op. cit.*, pp. 743–44.

[2] J. L. Gillson, "The Quartz Monzonite in the Pioche District, Lincoln County, Nevada; Its Differentiation and Endomorphism," *Amer. Mineral.* (In press.)

DISCOVERY OF SILURIAN FOSSILS IN FRENCH GUINEA[1]

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ABSTRACT

This is a description of the discovery of Silurian fossils in French West Africa, which for the first time offers definite information regarding the age of the sediments in the great area between the Atlantic Ocean and Timbuctu on the Niger and between the Senegal River on the north and the mouth of the Niger on the South. It describes the most southerly occurrence of Silurian fossils known in Africa and one of the three or four known occurrences of these fossils in all Africa.

INTRODUCTION

The recent discovery by the author of Silurian fossils in French Guinea pushes the boundary of the known Silurian much farther south in Africa and determines the age of a series of rocks of hitherto unknown age that underlie the great region known as French West Africa.

LOCATION OF FOSSIL BED

The discovery of these fossils was made early in 1918 by the writer of this paper while on a journey from the village of Kindia, on the Konakry-Niger Railway, to the Portuguese Guinea frontier. On arrival at the French post of Telimele in latitude 10° 54′ north and longitude 13° 02′ west, our caravan was halted to visit an excavation being made in search of copper ore in the valley of the Samarkou River, eight miles southwest of Telimele. This excavation had been made in the side of the valley, in horizontal, thin-bedded, gray shales containing iron pyrite which had been mistaken for copper ore. It was while examining these shales that large numbers of graptolites were discovered.

AGE OF THE GRAPTOLITES

The vast territory of French West Africa had up to that time furnished no Paleozoic fossil, and the most southerly point in Africa where the Silurian had been recognized was far to the north of

[1] Published with the permission of Mr. Russell Burrage.

French Guinea, so, realizing the importance of this discovery, we wrote to Professor Lacroix, of the Museum National d'Histoire Naturelle of Paris, and stated that one of the species appeared to us to be *Monograptus priodon*, a Silurian form. This letter was promptly published by Professor Lacroix in *Comptes rendus*.[1]

FIG. 1

On our return to Paris in May, 1918, the collection of fossils from the Samarkou River was presented to the Museum d'Histoire Naturelle of Paris, and for closer determination this was sent to Miss Gertrude L. Ellis, of Sedgwick Museum, Cambridge, England. Her report was incorporated in a paper presented to the Liège meeting in 1924 of the French Association for the Advancement of Sciences, and a résumé of this was published in 1925.[2]

[1] Joseph H. Sinclair, "Sur l'âge des grès de la Guinée française," *Comptes rendus de l'Académie des Sciences* (Paris, 1918), Vol. CLXVI, p. 417.

[2] Georges Lecointre and Paul Lemoine, "Sur les graptolites Gothlandiens de la Guinée française (Résumé)," *Compte rendu de la 18e Session* (Liège, 1924) *de l'Association française pour l'Avancement des Sciences* (Paris, 1925), pp. 387–88.

Miss Ellis determined the following species:

Monograptus riccartonensis Lapworth
Monograptus priodon Bronn.
Retiolites (gladiograptus) geinitzianus, Barrande

The *Monograptus riccartonensis* zone is near the base of the Wenlock stage,[1] a horizon approximately equivalent to the Niagaran (Middle Silurian) of Northeastern North America.

The Telimele strata belong to the formation called by French geologists *Grès siliceux horizontaux*, which covers nearly all of French Guinea and a large part of French West Africa. Hence it is probable that an enormous area of West Africa is underlain by rocks of Silurian age.

THE HORIZONTAL SILICEOUS SANDSTONES

The surface of French Guinea, with the exception of a narrow coastal plain bordering the Atlantic Ocean, is a series of uplands, each of nearly flat and slightly dissected surface, each limited by more or less pronounced escarpments, each underlain by horizontal or nearly horizontal layers of sedimentary and igneous rocks, and each occurring at varying altitudes above the sea, the most elevated, viz., the summit of the Fouta d'Jallon highland, having an elevation of about 5,000 feet above the sea. These features, coupled with the fact that the horizontal layers of sedimentary and igneous rocks underlying each upland or plainslike region are strikingly similar to those in adjoining uplands, make us suspect that we are dealing with a repetition of one and the same series of rocks in differentially uplifted blocks of the earth's crust.

The formation which apparently is repeated in each of the successive blocks, from near sea-level on the Atlantic Coast to high elevations eastward near the headwaters of the Niger and the Gambia rivers, is composed of three kinds of rocks, viz., sandstones, shales, and intercalated sills of diabase. The diabase has penetrated the sedimentary rocks as sills by a mechanical separation of the strata without producing any contact metamorphism or structural disturbance. These sills are very numerous, and of very widespread areal extent. They range from thin layers to thicknesses of 300 feet

[1] "The Zonal Classification of the Wenlock Shales of the Welsh Borderland," *Quar. Jour. Geolog. Soc.* (London, 1900), Vol. LVI, pp. 370–414.

and perhaps more. Their aggregate thickness is about equal to that of the sediments between which they have been injected. The diabase is the most striking geological feature of French Guinea. Owing to its association with weaker rocks, it has given rise to numerous cliffs in the interstream areas, and great cataracts in the rivers, with intervening long, narrow, lakelike stretches, where the rivers flow over the sedimentary rocks.

This group of sedimentary and igneous rocks has been named *Grès siliceux horizontaux* by the French geologists because of its widespread horizontality, and is called the "Saionia Scarp series" by the Geological Survey of Sierra Leone[1] because of its tendency to form great escarpments, some of which have cliffs with vertical faces of a thousand feet or more in height.

The base of the formation in the Saionia Scarp, where the Geological Survey of Sierra Leone has studied it, is reported to rest with "strong unconformity" upon members of a group of highly disturbed, old sedimentary and igneous rocks named the "Rokell River series." Of the upper limit of the *grès siliceux horizontant* we know nothing at present. To the north in Senegal it disappears beneath Tertiary sediments and to the east becomes covered by sands of the Sahara.

At least 600 feet of the formation are exposed in the Saionia cliffs on the Sierra Leone frontier near the Atlantic. This section includes a sill of diabase near the bottom of the formation, but omits one about 300 feet thick at the top. To the north and east the latter sill may be, and probably is, covered by additional sediments of the same formation. Owing to the great variation in the number of sills from place to place, and to the fact that a sill thickens or thins and disappears even over a limited area, it will doubtless be difficult to work out the thickness of the formation.

[1] Frank Dixey, "The Geology of Sierra Leone," *Quar. Jour. Geolog. Soc.* (London, 1925), Vol. LXXXI, pp. 195–222.

REVIEWS

Geologie Afrikas. By ERICH KRENKEL. Berlin: Gebrüder Borntraeger, 1925. Pp. x+461; plates, 22; figures, 105.

The first volume of Krenkel's *Geology of Africa* contains an introduction presenting the physiography of the African continent and the surrounding oceans, also a chapter upon the structure of Africa, and geologic discussions of the main divisions of Africa, each of which is treated as a separate unit.

The second volume will continue the description of the principal regions and close with a series of discussions of a general nature, with conclusions drawn from the geology of Africa.

The book divides Africa into the following principal regions which are treated separately: (1) Syria and Arabia, including the Sinai Peninsula, all of which the author includes in Africa; (2) Egypt and Nubia and the so-called Eastern Soudan; (3) Abyssinia and Somali Land; (4) East Africa; (5) the islands in the Indian Ocean; (6) South Africa; (7) the Congo Basin; (8) the Soudan; (9) the Sahara Desert; (10) the Atlas Mountains.

Each one of these regions is discussed with regard to its geologic formations, its volcanism, its structural geology, together with a sketch of its geologic history and a bibliography.

To judge from the first volume, the paleontologic side receives comparatively small space, but the economic features are better treated, as is also the physiography of the different regions and its relation to the vegetation.

A. C. N.

Ammonitenstudien. By MARTIN SCHMIDT. Berlin: Gebrüder Borntraeger, 1926. Pp. iv+363; plates, 1; figures, 35.

The author brings in the first part of the book the descriptions of a number of new species, or of old but insufficiently known species of ammonites from the Lower Triassic of Swabia. A large three-page plate at the end of the book and a number of text illustrations accompany these descriptions.

The second part of the book discusses the organs and means for locomotion as found in fossil and recent cephalopods. From the anatomy and histology of the recent types he draws his conclusions about the fossil forms.

In the final passages of the book Schmidt gives his opinion regarding the causes for the disappearance of the ammonites, and selects as most probable the changes in the temperature of the sea water. He believes that the frequent depressions of temperature during geologic time were more active in the destruction of ammonites than the possible appearance of enemies among marine animals.

Schmidt's book is No. 10 in *Fortschritte der Geologie und Palaeontologie*, edited by W. Soergel.

A. C. N.

Some Developments in Shallow-Water Areas in the Northeast of South Australia. By R. LOCKHART JACK. Geological Survey of South Australia, Department of Mines, Bulletin No. 11. Adelaide, 1925. Pp. 63; maps 4.

The object of this investigation was to find shallow sources of water in parts of the Great Artesian Basin where the Mesozoic artesian waters are too deep to be reached by the drill. The region is fitted for sheep-raising if a plentiful supply of water can be found. Jack's report suggests many possible sources of the shallow production which is wanted.

C. C. B.

The Geology of the Huntly-Kawhia Subdivision, Pirongia and Hauraki Divisions. By J. HENDERSON and L. I. GRANGE. New Zealand Department of Mines, Geological Survey Branch, Bulletin No. 28 (New Series). Wellington, 1926. Pp. 112; maps 15.

The Huntly-Kawhia subdivision is on the west coast of North Island, the northern boundary about 38 miles south of the city of Auckland. This bulletin is a report on the geology of the 1,790 square miles which comprise this subdivision. Mesozoic rocks are represented by 28,000 feet of sediments or more, the Upper Triassic, Jurassic, and Lower Cretaceous being present. A thickness of 2,000 feet of Cenozoic is made up of the Upper Eocene (?), Oligocene, Miocene, and Pliocene systems. The Upper Eocene (?) is coal-bearing. During the Pleistocene extensive faulting took place and non-marine sediments were laid down. Igneous intrusives pierce the Mesozoic rocks in some places.

By far the most important economic product is the coal of the Upper Eocene (?). It occurs in seams averaging 10 feet in thickness over large areas, and a considerable reserve is known. The geography, physiography, and other economic products of the subdivisions are discussed in short chapters.

C. C. B.